SURFACE MORPHOLOGY OF MARTIAN DEBRIS-COVERED GLACIERS: AN EVALUATION OF BOULDERS AND RIDGES AS POTENTIAL CLIMATE CHANGE INDICATORS

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ABSTRACT

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Observations of the mid-latitudes of Mars indicate significant populations of debris-covered glacial landforms. These features likely formed during the mid-to-late Amazonian when climate conditions supported the accumulation and glacial flow of ice. Morphological analysis of similar terrestrial glaciers suggests that their surface and englacial debris features preserve a record of episodic environmental change. However, glacial emplacement patterns responsible for martian mid-latitude glacial formation remain largely unknown. Here, we explore the hypothesis that surface morphology on martian remnant glacial landforms could preserve a record of climate fluctuations. We approach this hypothesis through an analysis of surface ridges and boulders on these debris-covered glaciers. Through the use of HiRISE images, we find that preliminary results of boulder breakdown rates are most consistent with episodic environmental change. Additionally, we find that CTX stereo images allow for the identification of a potential class of long wavelength surface ridges through spectral analysis. We hypothesize that these ridges may be related to a potential climate signal that could suggest a pattern of episodic environmental change, though further investigation is necessary. Our results support the use of surface morphology on debris-covered glacial landforms as a source of information for understanding martian mid-latitude glacial emplacement.

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ABBREVIATIONS

ADV	Antarctic Dry Valleys
CCF	Concentric crater fill
CTX	Context Camera
FFT	Fast Fourier Transform
Gyr, Gya	Billion years, billion years ago
HiRISE	High Resolution Imaging Science Experiment
K	Temperature in units of Kelvin
Kyr, kya	Thousand years, thousand years ago
LDA	Lobate debris aprons
LDM	Latitude-dependent mantle
LiDAR	Light Detection and Ranging
LVF	Lineated valley fill
MRO	Mars Reconnaissance Orbiter
Myr, Mya	Million years, million years ago
PAST	Paleontological Statistics Software
SHARAD	Mars Shallow Radar sounder

I. Introduction

The story of human understanding of water on Mars is one of technology and curiosity. One of our nearest planetary neighbors, Mars has experienced many of the same fundamental formation processes that have driven Earth's evolution. Yet, the planet is drastically different than our own, maintaining a land surface atmosphere over 100 times less dense than that of Earth and a cold, dry landscape with geologic structures that dwarf those we observe on our planet. Mars therefore presents an extremely unique destination for scientific discovery, offering insight into our own planet while challenging our ideas about fundamental geologic processes.

The search for water in its various forms on Mars has existed at the forefront of human inquiry of the planet. Though the surface of Mars today is extremely cold and dry, numerous landforms indicate that water has played a significant role in shaping the landscape throughout geologic history. Present geomorphological evidence of surface water in the past includes (but is not limited to) channels, deltas, and alluvial fans (Baker, 2006). While we now know that water once flowed across the surface of Mars, it remains unknown if water provided a habitat for life. Investigations now turn to the potential of ice as a climate record to explore the history of water on the planet and how these results could alter the future relationship between life and Mars.

Beginning with early observations from the Viking Orbiter images in late 1970s, studies of the mid-latitudes of Mars have indicated significant populations of glacial landforms exhibiting characteristics of viscous flow (Plaut et al. 2009). Though initial Viking-based observations interpreted these features as debris flows with ice content as low as 10%, more recent studies employing new radar technology indicate that they consist predominately of water ice (Pierce et al., 2003; Plaut et al., 2009). The presence of significant volumes of water ice at mid-latitudes transforms the potential of missions in these regions by providing a potential water resource and sites to study the climatic evolution of the planet. Though these glacial features have impressive implications for expanding remote work on Mars and in situ exploration, our understanding of their formation history is presently limited.

A. Previous work.

The study of geomorphology addresses the nature and origins of landforms and landscapes and has provided insight into processes and form on both Earth and Mars. As a result, it is a powerful method of scientific inquiry on both planets. Its application to the martian landscape often relies upon established process and landform relationships on Earth. Observations on terrestrial debris-covered glaciers suggest that analysis of the surface morphology on this class of landforms could reveal information about glacial and climatic history (Mackay et al., 2014). While work on Earth has the advantage of large data sets of varied origin (e.g. ice core drilling, borehole temperatures, etc.), recent advancements in camera and radar technology make the study of surface morphology on Mars a realistic and useful approach.

Our work primarily relies on images from the High Resolution Imaging Science Experiment (HiRISE) and Context Camera (CTX) aboard the Mars Reconnaissance Orbiter (MRO). This toolset allows us to observe surface morphology on various scales, ranging from small-scale objects on debris layers to wide-area views of kilometer-scale features. Though previous studies have used these imaging resources to constrain the age of martian debris-covered glaciers (Fassett et al., 2014), no work thus far has resolved the question of mid-latitude ice deposition history.

B. Brief history of water on Mars

Though rife with features that indicate water played a significant role in shaping the landscape, the history of water on Mars remains relatively enigmatic. Observations of landforms and deposits understood as resulting from fluvial and glacial processes reveal that Mars once sustained hydrologic features unsupported by its current hyper-arid landscape (Baker, 2006).

Following the idea that there was once flowing water on Mars, we must now question where it went and why we observe such a dry desert present-day climate. Studies have explored a range of processes for the removal of surface water on Mars, including movement into the atmosphere, underground aquifers, and shallow ice deposits (Cravens et al., 2017; Fox et al., 2015; Hodges 2002). Essential to a discussion of this redistribution of water on Mars is an understanding of the variability of the planet's climate over geologic time.

i) Role of orbital parameters. Mars experiences oscillations in its orbit due to gravitational interaction with other planets and the Sun, resulting in significant climatic shifts (Mellon et al., 1995; Laskar et al., 2004). These orbital parameters include eccentricity, precession, and obliquity, and each have an impact on martian climate. Eccentricity describes the shape of Mars' orbit and influences the magnitude of the variations in solar radiation within seasons (JeongAhn et al., 2015; Armstrong et al., 2004). Also influencing magnitudes of solar radiation, precession is the change in the orientation of Mars' rotational axis, affecting the contrast between seasons (Armstrong et al., 2004). The third parameter, obliquity, or axial tilt, has the most significant impact on climate, determining the strength of seasons and latitudinal distribution of solar radiation (Segschneider et al., 2005; Armstrong et al., 2004; Laskar et al., 2004).

Though Mars undergoes these oscillation variations on timescales similar to Earth's, the ranges of these variations are much larger on Mars than Earth (Laskar et al., 2004; Kreslavsky et al., 2003). Studies have described the obliquity of Mars as chaotic, ranging from 0º to over 60º (Laskar et al. 2004). Earth, however, experiences variations of about +/– 1.3º around a mean value of 23.3º (Laskar et al., 2004). As a result, it is possible that effect of variations in orbital parameters on martian climate are significantly more intense than on Earth. Studies of these orbital and spin axis controls on climate indicate that obliquity dominantly controls the transportation and distribution of water between atmospheric, surface, and subsurface reservoirs (Laskar et al., 2004).

Due to the chaotic nature of proposed obliquity values, variations have only been constrained for the past few million years, though a solution has been suggested for the evolution of Mars' spin over 10 to 20 Myr (million years) (Laskar et al., 2004; Madeleine et al. 2009). Presently lacking precise values for past orbital configurations over geologic timescales, other approaches to the study of the evolution of the martian hydrologic cycle time are useful for understanding previous climatic conditions on Mars.

Given that current conditions are not indicative of all of martian geologic history, an overview of ancient and recent climate conditions provides insight into the role and redistribution of water throughout time. The geologic history of Mars is generally divided into three broad epochs including the Noachian (prior to ~3.7 Gya (billion years ago)), Hesperian (~3.7 to 3.0 Gya), and Amazonian (~3 Gya to present). Water-generated landforms indicate that water and ice were present on the surface during each of these epochs (Mellon and Jakosky, 1995). Crater statistics have been used to further break down the chronology of water activity during these periods, associating densely cratered uplands with ancient Noachian processes, significantly lower impacts cratering rates with the Hesperian, and relatively lightly cratered surfaces in the Amazonian (Baker, 2001).

ii) Ancient water cycle. Though it has been the focus of extensive research, the nature of Mars' climate during the high-impact Noachian epoch remains a subject of debate. Evidence of fluvial and lacustrine environments suggests that the early Noachian climate of Mars (first ~20% of its history) supported a hydraulic system very different from what we see today (Marchant et al., 2007). It is clear that aqueous alteration influenced the early martian surface. However, limitations in present observations have left significant uncertainties in characterizing this environment. Questions concerning the intensity and frequency of warming episodes, the distribution of water into its various forms (solid, liquid, gas), and precise atmospheric composition are the subject of much disagreement (Wordsworth et al., 2015).

Hypotheses range from a “warm and wet” (Craddock et al., 2002) to a “cold and icy” (Toon et al., 2010) ancient environment. While the Earth’s crust is relatively young and consequently preserves little evidence of early impact bombardment, the surface of Mars hosts extensive evidence of Noachian-aged bombardment (Abramov et al., 2016). Studies of these bombardment features have sought to evaluate the influence of impact forcing on hydrothermal environments during the Noachian, suggesting that it may be one mechanism of episodic melting in a cold and icy scenario (Abramov et al., 2016; Wordsworth et al., 2015). The idea is that this sporadic melting combined with seasonal melting of snow and ice and water from aquifer discharge provided the water required for observed aqueous erosion (Toon, Segura, and Zahnle, 2010).

Other studies have suggested a very different idea, concluding that rainfall and surface runoff provide the best explanations for the surface features characteristic of the cratered highlands. Supporters of this scenario dominantly cite ancient valley networks as evidence of a warm and wet early climate (Craddock et al., 2002). Whether this early Mars was “warm and wet” or “cold and icy” remains a subject of debate within the history of water on the landscape.

iii) Recent water cycle. Low-temperature, low-pressure, dry conditions with significant eolian activity have defined the martian environment since the end of the Hesperian (~3 Gya) (Dickson and Head 2009; Marchant and Head 2007). While extremely cold, hyperarid conditions characterize current observations of the planet with water sequestered in the regolith-cryosphere, studies suggest a number of periods of ice accumulation and geographic redistribution within the Amazonian (Fastook, Head, and Marchant 2014; Head et al., 2010). Present understanding indicates that the formation of ice-rich features during the Amazonian may characterize much of the water cycle activity during this period.

Notably, present-day pressure and temperature conditions do not support the formation of surface ice where we observe it in the mid-latitudes today (~ ±30 and 50° latitude) (Levy et al., 2014). Previous climate conditions that were conducive to the formation of this mid-latitude ice may have been occurred in episodes throughout much of the Amazonian (Laskar et al., 2004).

While we do not observe this environment today, evidence of this climate persists through present day in many observable features, including mid-latitude (~ ±30 and 50° latitude) remnant glacial landforms (Fassett et al., 2014). This category of debris-covered glaciers (Holt et al., 2008) includes three primary features: lineated valley fill (LVF), lobate debris aprons (LDA), and concentric crater fill (CCF). Crater statistics have constrained mid-latitude glacial emplacement to the mid-to-late Amazonian (~1 Gya to ~100 Mya) (Berman et al., 2015), though exact time of formation remains an area of active research.

Providing insight into martian hydrologic and climatic cycles, an outline of this formation history in a different climate is essential to the advancement of work on Mars. The implication is that a deeper knowledge of these processes will help us understand the nature of water on the planet and its role in the support of potential life and in situ exploration of the planet.

iv) Mid-latitude glacial landforms. Studies of LDA, CCF, and LVF origin suggest that ice accumulated along sheltered alcoves and flowed downslope into the surrounding terrain, away from scarps (steep slopes) or highland massifs (Head et al., 2005). LDA, CCF, and LVF serve as some of most prominent examples of ice-related flow on Mars, yet the details of the evolution of their formation including ice accumulation patterns and the sources and relative inputs of debris remain unknown.

A number of criteria have been suggested for the recognition and identification of these debris-covered glacial deposits. These parameters include (1) the presence of alcoves in mesas, valley walls, or massif walls that could have served as ice accumulation zones, (2) parallel or arcuate ridges emerging from these alcoves that are interpreted as flow-deformed ridges, (3) minor depressions between these ridges and the alcove walls cause by the sublimation of previously stable snow and ice, (4) tightening and folding of parallel curved ridges resulting from constraints on debris-covered glacial flow, (5) broadening and opening of ridges where ice flow was unhindered, (6) merging of ridges where flows converge (7) integrated valley glacier systems extending for tens to hundreds of kilometers formed by the convergence of LVF, LDA, and/or CCF, (8) sharp, narrow plateau remnants between valleys, and (9) convex-up surface topography with a parabolic down-slope profile (evident in **Fig. 7** and **Fig. 1**, respectively) (Head et al., 2010). Two of the most distinct and useful characteristics for the identification of LDA that we primarily rely on in our study are convex-upward surfaces and evidence of flow extending from massifs and escarpments.

Recent studies have suggested LVF, LDA, and CCF cover ~0.5% of the global surface area of Mars, with much of their formation history remaining unknown (Levy at al., 2014). Ongoing work aims to explain the origin and history of this ice. Here we evaluate surface features on debris-covered ice and their potential to shed light on the nature of martian glacial deposition cycles to further our understanding of past conditions on Mars.

C. Objective

The gap in understanding between LDA emplacement and the climate conditions responsible for their formation provokes a fundamental question: did they form episodically, continuously, or somewhere along this spectrum? The first goal and required step in reaching the primary objective of this study is to evaluate methods of characterizing relationships between LDA surface ridges. The establishment of a useful approach of analyzing the frequency and patterns of these ridges is integral to understanding their origins and the processes that form LDA. The ultimate implication is that with a better understanding of LDA formation history, we can infer key information about past conditions on Mars and possible future targets for in situ missions.

Our study uses HiRISE and CTX images to analyze small and large-scale surface morphology to investigate flow history. Specifically, we characterize boulder size distributions and surface ridge patterns to evaluate proposed formation mechanisms. Synthesizing our results from the study of these different surface features, we present new evidence to infer changes in glacial emplacement.

II. Background

Found in the mid-latitudes of Mars, LDA result from the accumulation and flow of thick (hundreds of meters) debris-covered ice (Parsons and Holt, 2016). While polar ice caps store the majority of ice on Mars, the sum of these debris-covered landforms (CCF, LVF, and LDA) represents a significant volume of the global ice budget (Levy et al., 2014). Measurements of ice volumes and ice equivalents on Mars and Earth are presented in **Figure 1**. Specifically, erosion studies suggest that LDA may have been the largest, most active of these debris-covered landforms (Levy et al., 2016). Knowing these glacial features play an important role in the distribution of ice on Mars, further study of their formation conditions and processes could provide valuable insight into both the past and future climate of the planet.

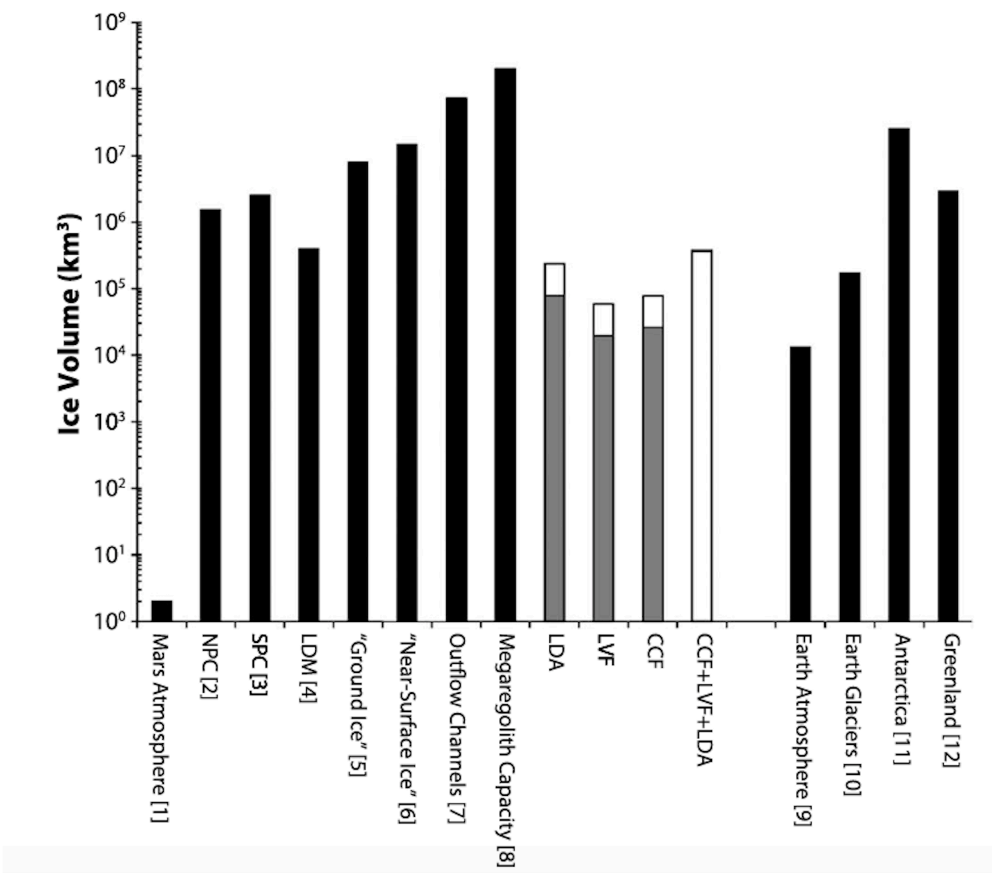

Figure 1. Inferred and measured volumes of ice and water vapor-bearing units (ice equivalents) on Mars and Earth (from Levy et al., 2014).

Studies of insolation patterns and surface topography have highlighted the sensitivity of near-surface ice to changes in climatic conditions (Kreslavsky et al., 2008; Humlum, 1998). Building on this idea and observations on terrestrial Mars-like environments, we hypothesize that LDA topography and surface morphology could contain a record of climate fluctuations on Mars. Numerous other studies support and explore this hypothesis (Fassett et al., 2014; Mackay et al., 2014; Grindrod et al., 2011), though no study has conclusively linked LDA surface morphology to a pattern of glacial emplacement.

Residing on glaciers as surface features and potentially moving at rates influenced by glacial flow (Hubbard et al. 2014), martian glacial surface boulders and ridges may reflect information about the rate of glaciation. Because boulder erosion rates likely exist somewhere in between high 10^{-1} m/Myrs and low 10^{-2} m/Myr estimates (Levy et al. 2016), they breakdown on timescales sufficient to affect population distributions on the 100 Myr to ~1 Gyr surface age of LDA, LVF, and CCF (Fassett et al. 2014). Therefore, boulder breakdown rates on Mars may provide insight into martian glacial history as terrestrial boulder breakdown rates have on Earth (Putkonen et al. 2014).

Additionally, an analysis of surface ridges on LDA may reveal new information regarding the climatic conditions that drive these diverse geologic features. To determine if surface ridges could yield a reliable climate signal, we first need to understand the relationships between different kinds of ridges and their respective formation mechanisms. If we understand the origins of different ridge types and can associate the formation of any with reduced net ice accumulation and renewed net ice accumulation cycles, we can subsequently consider the possibility of a climate signal.

An understanding of LDA formation history through the lens of surface morphology would provide insight into not only climate changes in the Amazonian, but also on the nature of martian hydrological system through time. Current LDA understanding dominantly relies on the analysis of morphologic features and geographic distribution patterns, resulting in both useful data and persisting questions regarding mechanisms and timing of formation.

A. Lobate debris aprons

LDA typically exist as gently sloped (<5º) convex-upward aprons adjacent to massifs and escarpments (Fastook et al. 2014; Plaut et al. 2009) (**Fig. 2**). Longitudinal profiles (**Fig. 8**) of LDA flow features present a convex shape some authors have explained through debris apron rheology: a material with high yield strength in this case likely the results from an ice-rich composition (Li et al., 2005).

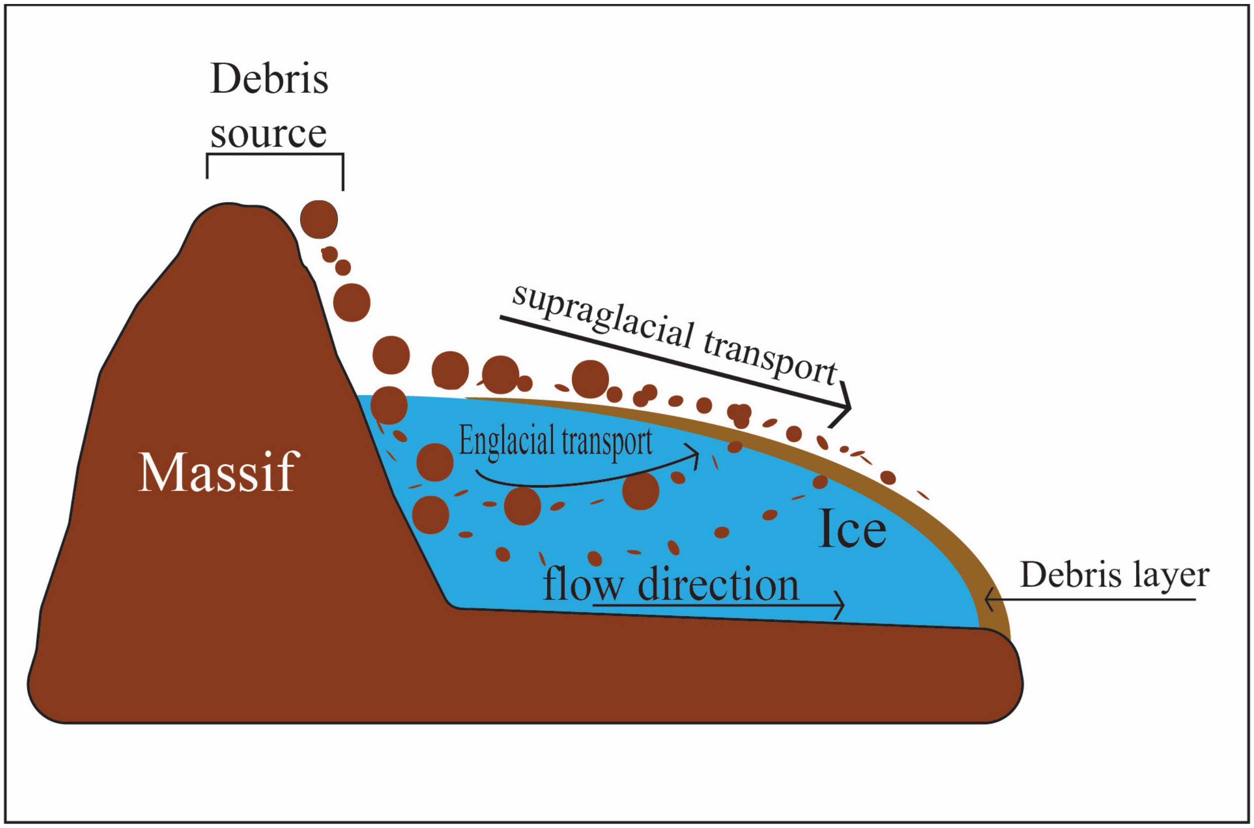

Figure 2. Lobate debris apron illustration showing supraglacial and englacial transport of debris as ice accumulates and flows. Debris size and vertical scale are exaggerated to show transport.

Capable of penetrating though several kilometers of ice, the SHARAD subsurface radar sounding experiment on MRO provides images of the subsurface with a vertical resolution of 15 m (Plaut et al., 2009). SHARAD observations of LDA show radar properties consistent with a water ice composition and indicate a structure of thick ice (Plaut et al., 2009). Atop this thick ice is a surface cover of thin (meters to tens of meters) debris (Holt et al., 2008; Plaut et al., 2009). Observations on terrestrial analogues indicate that this layer of debris on LDA likely reduced ablation of underlying ice, allowing them to endure through presently unstable pressure and temperature conditions (Fassett et al. 2014; Mackay et al. 2014; Konrad et al. 1999). Ice flow models explain that this reduced ablation has preserved LDA over times scales on the order of hundreds of millions of years and support the hypothesis that LDA, CCF, and LVF are remnants of a much larger regional ice sheet (Fastook, Head, and Marchant 2014; Plaut et al. 2009).

Questions of ice origin(s), formation timing and process, ice-flow dynamics, and debris transport (englacial and supraglacial) drive current research. The implication is that an understanding of LDA morphology formation mechanisms will help determine if they preserve a record of climate change on Mars. Resources including radar, topographic data, and high-resolution images offer new opportunity for study, propelling our understanding of these features and the history of martian climate.

B. Setting

The distribution of LDA is generally restricted to mid-to-high-latitudes, with significant populations in the fretted terrain of the northern hemisphere and near the Argyre and Hellas Basins regions of the southern hemisphere (Pierce and Crown 2003). Concentrated into two main latitudinal bands (~25º wide centered on 40º N and 45º S) with notable size variations existing between northern and southern hemisphere formations (Li, Robinson, and Jurdy 2005), studies have provided a number of explanations for the pattern and processes behind their formation. **Fig. 3** provides the distribution of LDA, CCF, and LVF mapped by Levy et al. 2014, displaying two clear concentrated latitudinal bands. This study will focus on LDA in the eastern Hellas region (Hellas Basin labeled in **Fig. 3**) of Mars – an area notable for its fluvial and glacial features.

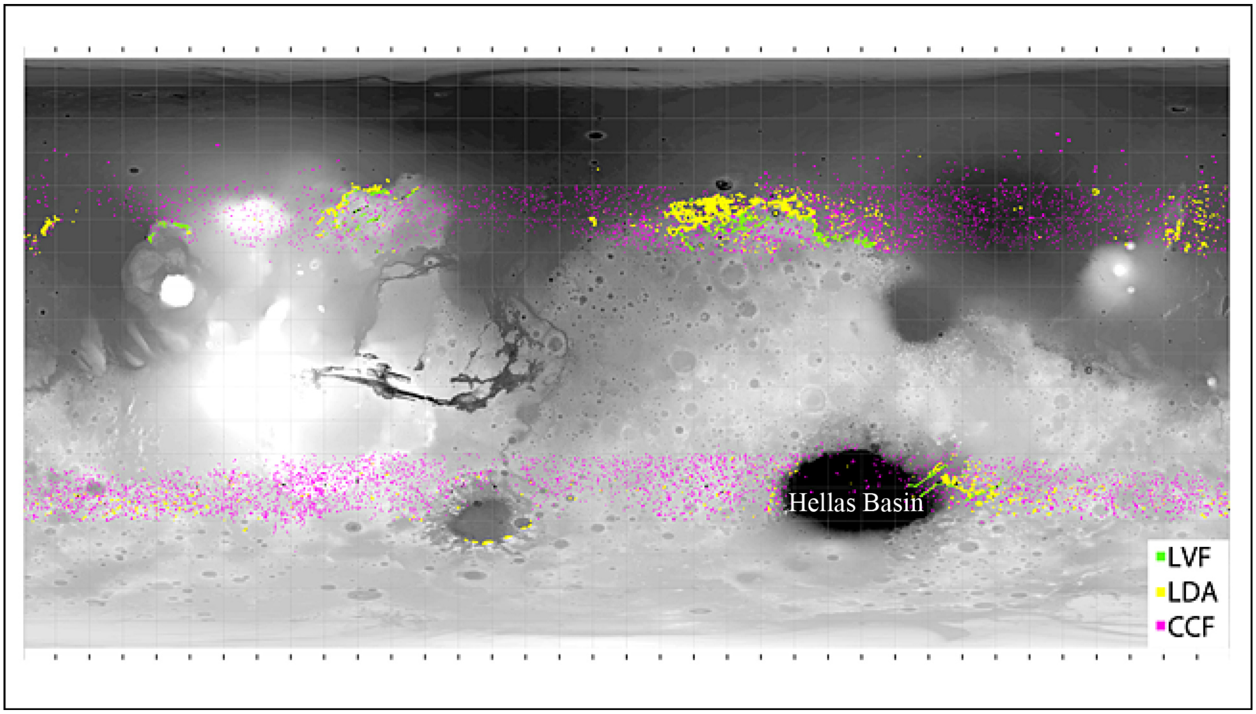

Figure 3. A mapped distribution of LVF, LDA, and CCF (from Levy et al., 2014).

C. Conditions of LDA formation

Current year-average surface temperatures on Mars fall well below the freezing point of water (0 °C), resulting in extensive permafrost cover (Marchant and Head 2007; Kreslavsky, Head, and Marchant, 2008). However, temperatures rise above 0 °C during the summer in the mid-latitudes.

Exact temperatures differ geographically throughout Mars as they do on Earth, resulting in a range of values influenced by factors such as latitude, season, and topography (Marchant and Head, 2007). However, this collection of current environments still does not explain why some LDA exist at latitudes where surface and ground ice should not presently accumulate (Madeleine et al., 2009; Fassett et al., 2014). This leads to an essential question: under what conditions did then form and when did these conditions exist? An understanding of how these glacial features formed requires a look into martian climate change, promoting investigations into time, process, and the future of climate on Mars.

Obliquity-driven climate change on Mars likely results in glacial and interglacial periods, with ice-rich features serving as some of the most sensitive indicators of these climate cycles (Head et al., 2005; Kreslavsky et al., 2003). As a result, we can expect the effects of orbital-driven changes on Mars to be significant in the formation and present day form of LDA. As previously discussed, changes in obliquity affect the latitudinal distribution of solar radiation across the planet, with periods of higher obliquity favoring ice deposition in lower latitudes (Nakamura and Tajika 2003; Fassett et al. 2014). Throughout the Amazonian, these changes likely propelled the transport and redistribution of ice from the polar caps to the mid-latitudes (Marchant et al., 2007). While Mars is currently in a period of relatively low obliquity, studies suggest higher values in the mid-to-late Amazonian, resulting in a climate different from that which exists presently (Costard et al. 2002). However, due to the chaotic variations in obliquity over large time scales, the timing within the Amazonian of this suggested high obliquity period for LDA formation remains unknown. Most recent studies agree that LDA are relatively young features, forming in the mid-to-late Amazonian (~1 Ga to ~100 Ma) (Fassett et al. 2014; Fastook and Head, 2014) when obliquity values in excess of 35º supported the formation of large ice deposits at mid-latitudes (Head et al., 2005).

Until recently, three major hypotheses existed to describe the formation of LDA: (1) ice-lubricated debris exhibiting viscous flow, (2) alpine-type valley glaciers, or (3) remnants of a more extensive ice sheet (Fastook et al. 2014). Recent climate and glacial flow models indicate patterns of regional ice accumulation (Fastook et al. 2014; Madeleine et al. 2009), supporting the idea that LDA are remnants of a regional ice sheet collapse. Presently, this model provides the best framework for LDA formation and should undergo continued testing.

To understand formation timing and climate conditions, studies have evaluated various LDA parameters including (but not limited to) height, lateral extent, and ice volume (Levy et al. 2014; Fastook et al., 2014). The idea is that by understanding and using the present-day nature of LDA as parameters in LDA formation modeling, studies can better predict the climate conditions during their formation and when these conditions may have existed. Assuming a regional ice sheet model, modeling of LDA formation requirements suggest temperatures for LDA formation conditions in the range of 200 to 204 K and typical sublimation rates in the range of 6–14 mm/a (Parsons and Holt, 2016; Fastook et al., 2014).

While existing models using geologic features provide valuable information for placing the formation of LDAs in the Amazonian (Berman, Crown, and Joseph 2015), current models of LDA rates of formation deliver conflicting time requirements for LDA development. Studies produce formation time estimates ranging from approximately 500 kyr (Fastook et al., 2014) to longer than 100 Myr (Parsons et al., 2011). Crater studies indicate that LDA formed over a period of at least ~600 Myr (Fassett et al., 2014), though have not provided conclusive answers regarding the dynamics of ice flow. In addition to this disagreement regarding duration of formation, the question of whether these LDA formed episodically, continuously, or somewhere along this spectrum remains unanswered.

D. Terrestrial analogues: Antarctic Dry Valleys

One of the most useful methods of understanding LDA and their formation mechanisms is through the lens of analogous features on Earth. Similarities between terrestrial and martian debris-covered glaciers derive from similarities in climate; a hypoarid, hypothermal climate controls processes on both present-day Mars and in the Antarctic McMurdo Dry Valleys (Marchant et al., 2007). These climatic conditions support the comparison of cold-based glaciation on both planets and result in debris-covered glaciers consisting of similar ice content (Mackay et al., 2014; Plaut et al., 2009). Studies have employed numerous rheological models based on terrestrial debris-covered glaciers to study the internal structure and climate conditions for the formation of glaciers on Mars (e.g. Colaprete and Jakosky, 1998; Pierce and Crown, 2003; Whalley, 2003).

LDA formed during periods (or possibly a single event) of Amazonian glaciation when erosion rates were similar to those on terrestrial cold-based glaciers (Levy et al., 2016). The similarities between LDA and debris-covered glaciers on Earth support the idea that the accumulation and flow of glacial ice produced LDA, LVF, and CCF. After or during this emplacement, debris covered these glacial deposits, producing the observable forms we see today (Li et al. 2005; Levy et al. 2016). Similarly, a protective layer of debris reduces ice sublimation on debris-covered glaciers in the Antarctic Dry Valleys (ADV) (Fastook et al., 2014).

Mullins and Friedman Glaciers in the ADV serve as two of the most useful terrestrial analogues, exhibiting viscous flow features similar to those observed on LDA (Mackay et al., 2014; Head et al., 2010). Notably, Mackay et al. (2014) uses englacial and supraglacial debris observations to reach conclusions about the history of the accumulation and flow of these glaciers, highlighting the potential of martian LDA surface ridges.

Studies have also successfully used boulder breakdown rates to infer information about environmental history on Earth (Bockheim, 1982, 2002, 2010; Ehlmann et al., 2008; Putkonen et al., 2014). Specifically, boulder studies in the ADV have indicated an observable relationship between the degree of surface boulder weathering and the age of geomorphic surfaces (Bockheim, 1982, 1990, 2002). The success of these studies in Mars-like climates provides further support for the application of these methods on LDA, LVF, and CCF.

E. Boulder distribution

Transported on the glacier surface and likely englacially, boulders may have the potential to reflect information about the rate of glaciation. Hubbard et al. (2014) uses HiRISE images to analyze boulder populations on martian glacial features and concludes that glacial-like features have the ability to transport debris and that boulder populations may have experienced passive redistribution. Expanding on the Hubbard et al. (2014) suggestion that glacial flow has affected boulder population distribution, this study aims to use boulder size distribution to (1) constrain the history of glacial accumulation and flow, (2) assess rates of boulder breakdown, and (3) determine if glacial emplacement was continuous, episodic, or sporadic over the last ~1 Gyr. Because HiRISE and CTX imaging allowing for direct measurement of surface features on LDA, an exploration of boulder size distributions via measurement of individual boulders may prove useful in inferring changes in glacial flow.

We hypothesize six general pattern possibilities could exist and account for differences in boulder size distribution with distance down-glacier: uniform, linearly decreasing, exponentially decaying, stepped size/decreasing, and peaked. **Fig. 4** presents these idealized predictions.

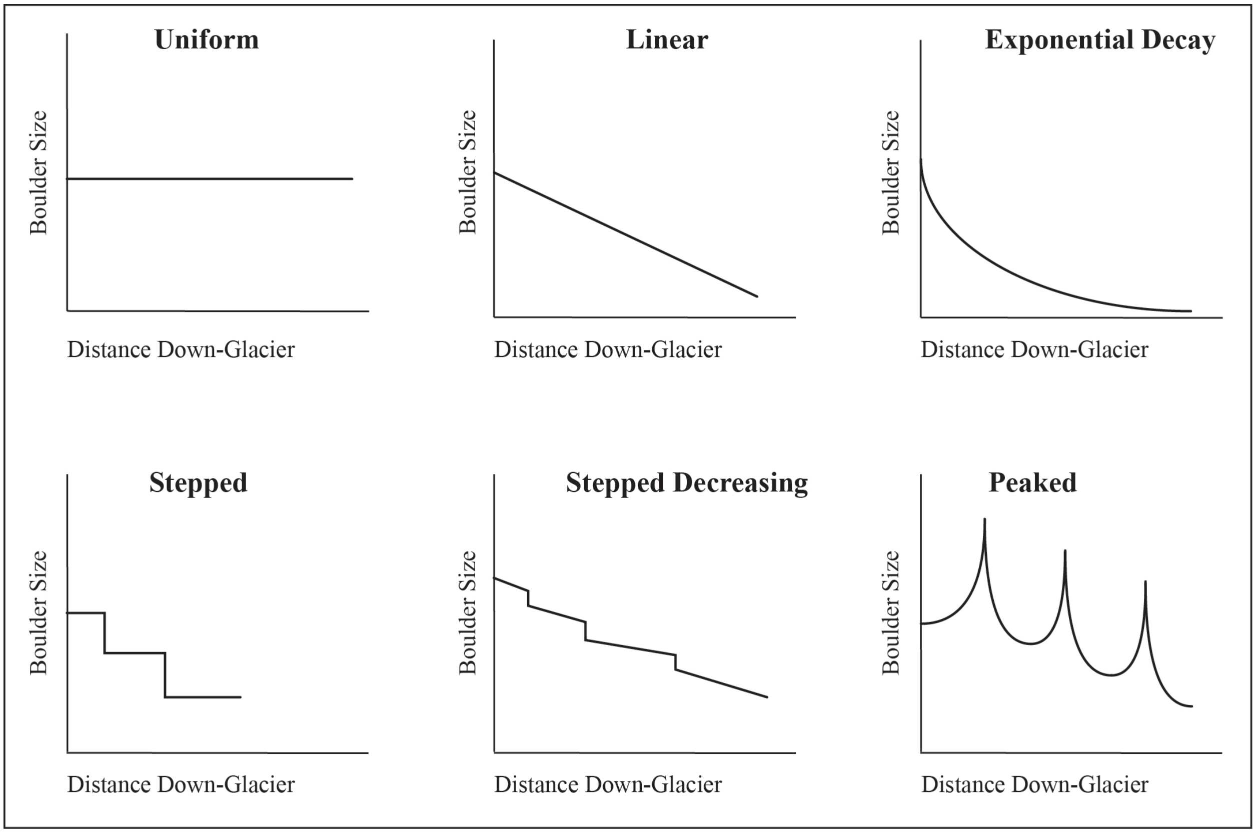

Figure 4. Idealized possible scenarios for boulder distribution.

A uniform boulder size distribution could result if weathering has not affected surface boulder sizes or if these measured boulder populations developed after glacial accumulation and flow ended. While this distribution would not provide significant information for constraining glacial formation history, it would shed light on glacial debris sources and processes of debris emplacement. Specifically, it would show that the origin of these boulders is not erosion in the glacial accumulation zone. Given our hypothesis of relatively recent glaciation and slow erosion, we do not expect our results to present a uniform distribution. Furthermore, preliminary observations indicate that this is an unlikely result considering the dense local populations of boulders existing on these landforms.

A linear distribution would confirm that there exists a relationship between ice accumulation and boulder size, specifically indicating that rates of boulder breakdown are greater than those of glacial flow. A consistent linear relationship could signal continuous rates of boulder breakdown and glacial flow, providing a potential framework for glacier emplacement. Notably, this distribution would indicate minimal amounts of englacial boulder transport, with supraglacial movement as the dominant form of boulder conveyance. This would deviate from recent terrestrial models that suggest englacial transport is an important process on debris-covered glaciers (Mackay et al. 2014).

A pattern of exponential decay would be most consistent with previous observations of boulder size distributions (Golombek et al., 2003). This boulder size evolution would indicate that flow rate and boulder breakdown rate have changed relative to each other over the time frame represented in our measurements.

A stepped size distribution would have important implications for climate change by indicating the possibility of episodic glaciation. During periods of reduced net ice accumulation, boulders sit on the surface of glaciers, weathering in their deposited position until a period of accumulation conveys them down-glacier. As these boulders are transported away during periods of glacial advance, new, larger boulders that have not been exposed and eroded replace them. As a result, we could expect a stepped size distribution indicated episodes of high flow rate and relatively slow boulder breakdown rates followed by long pauses in glacial advance during which boulders could weather in place and become smaller. This interplay of glacial advance and hiatus could have extensive implications for understanding Amazonian climate cycles.

Similarly, a peaked size distribution would also suggest pulses of glacial advance. This pattern would present a similar scenario of in situ boulder weathering followed by transport.

However, this result could also reveal a significant role for englacial debris transport within these features. If boulders are transported englacially, intersecting the surface upon recent exposure by sublimation, we could expect them to be larger because they have not had the opportunity to weather over extensive time periods on the surface. The intersections of englacial debris with LDA, LVF, and CCF surfaces could produce the peaks in boulder size observed in this distribution. It is also possible that the debris source delivered boulder populations of different sizes and the peaks and troughs reflect the variation of initial debris size.

Results producing one (or a combination) of these potential patterns would provide information integral to an understanding of glacial flow history and the relationship between flow rate and boulder breakdown.

F. LDA surface ridges

Because spin and orbital parameters indicate current insolation variations on Mars differ from long-term averages over the Amazonian (Fassett et al., 2014) and LDA exist at presently unstable conditions (Fassett et al., 2014), an exploration of climate information sources becomes essential to an understanding of processes on the planet. Observations from HiRISE and CTX images reveal clear surface ridges of presently unknown origin. These lineated ridges on LDA, LVF, and CCF surfaces extend from previous zones of ice accumulation at the base of alcoves in mesas, valley walls, or crater walls to the toe of these features. This research seeks to understand environmental conditions of LDA surface ridge formation and evaluate these surface features as a potential climate archive.

Ridges reside on LDA as a distinct, observable surface texture (**Fig. 5**). The long axes of these curved surface features are generally oriented transverse to the direction of LDA flow, though variations in orientation range significantly from perpendicular to parallel to flow direction.

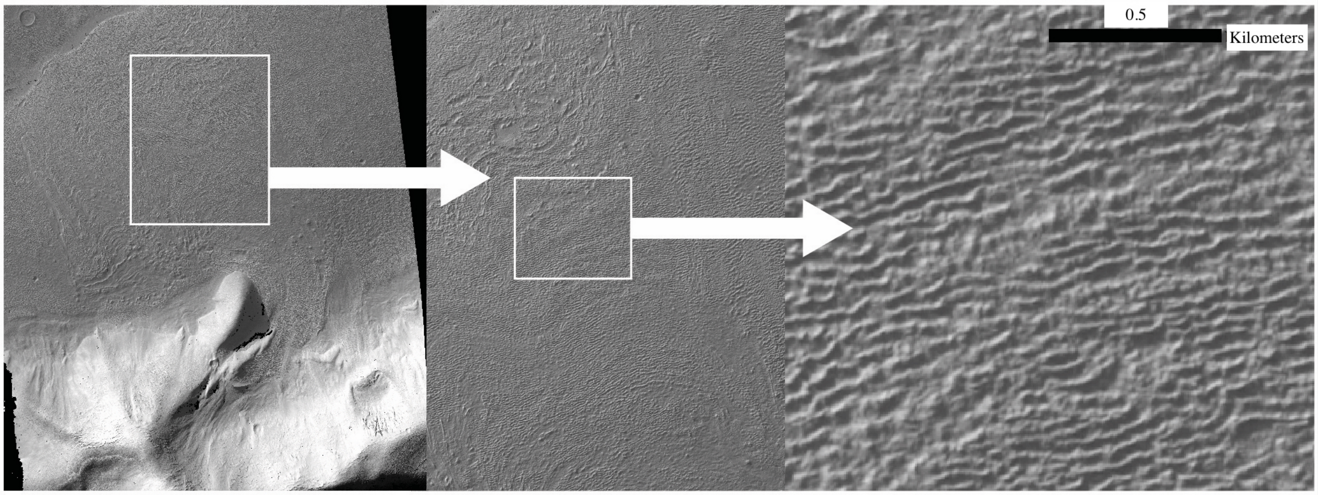

Figure 5. Example of surface ridges on LDA D09_030776_1349

Drawing from observations of surface morphology on Mullins and Friedman Valley glaciers (Mackay et al., 2014), we hypothesize that LDA ridges do not derive from a single origin, but rather result from a number of possible processes. Other studies support this multi-type framework (Pierce and Crown 2003), though they have yet to provide a consistent characterization of ridge types and origins. Observations and modeling thus far provide various hypotheses to explain LDA ridge formation. Suggestions of ridge formation mechanisms include (1) shorting from downslope movement (Pierce and Crown 2003) (2) aeolian processes (Pierce and Crown 2003) (3) viscous buckle-folding (Frehner et al., 2015) (4) englacial structure and debris transport (Mackay et al. 2014).

A similar list of formation mechanisms holds true for terrestrial analogues; Mackay et al. (2014) notes that while major ridges result from englacial debris transport, locally discontinuous surface ridges may be shortening features developing from compressive flow. The debris bands on debris-covered glaciers on Earth including Mullins and Freidman glaciers in the Antarctic Dry Valleys likely originate from the englacial transport of rock fall from rock cliffs at valley heads (Mackay et al. 2014). This rock fall exists as supraglacial debris that accumulates during periods of low ice accumulation, is buried upon onset of increased accumulation, and transported englacially, producing ridges at intersections with the ice surface (Mackay et al. 2014). The exact percentage of rockfall that exists solely as supraglacial debris on these glaciers is unclear (Mackay et al. 2014).

These observations of englacial debris bands and surface ridges on terrestrial debris-covered glaciers in the Antarctic Dry Valleys indicate episodic environmental change in the past (Mackay et al. 2014). Because these cold-based debris-covered glaciers share fundamental similarities with martian LDA features (Head et al. 2010), the finding that they may be useful climate archives highlights the potential of LDA surface ridges to serve as paleoclimate indicators. ADV conditions maintain many similarities with the present-day hyper-arid, cold desert (Marchant and Head 2007) climate on Mars and subsequently serve as a useful analogue. However, the significance and process of englacial debris transport on LDA is presently unknown.

Drawing from the methods employed on Mullins and Friedman Glaciers (Mackay et al. 2014), this research examines the frequency and spacing of surface ridges on north and south flow paths of LDA. The objective is to determine an effective method of ridge analysis and to use these results to identify periods of glacial advances and/or pauses. The implication is that this insight can then be used to draw conclusions regarding processes of LDA formation and the history of glacial development on Mars.

Previous studies indicate that LDA surface ridges may serve as climate signals, citing repeated changes in climate as a possible mechanism for their formation (Grindrod and Fawcett 2011). However, uncertainties in understanding the causes of LDA ridges, the climate information they may hold, and the best methods of analysis continue to make these ridges a relevant and promising area of research.

If we determine that there is a ridge type produced by changes in ice accumulation and ablation, we would then need to observe a strong correlation between the number and spacing of these ridges down-glacier across our sample of different LDA. Results presenting a pattern of periodic ridges formed by changes in ice accumulation rates across LDA would indicate a possible widespread, consistent signal of environmental change. Should ridge analysis indicate that these surface bands serve as climate archives similar to those on terrestrial debris covered glaciers (Mackay et al. 2014), their importance to future study and exploration of Mars would be vast.

III. Methods

A. Boulder measurements

This study uses HiRISE images with a resolution of 25 cm/pixel to accurately measure individual boulders with a diameter size ≥1 m. Following proven methods employed by Golombek et al. (2003), we used manual measurement of boulders to calculate size frequency distributions. All boulder measurements on a given LDA, LVF, or CCF were made within 50 m of a central flowline determined by the locally highest convex flow path. Boulders are easily distinguishable in the HiRISE images as starkly contrasted dark and light adjacent pixels (an interplay of solar illumination and boulder shadow) (**Fig. 6**). Boulder size was determined by the linear distance of the illuminated boulder face perpendicular to the direction of incoming sunlight. Measurements were made in ArcMap using the polyline tool and exported for analysis.

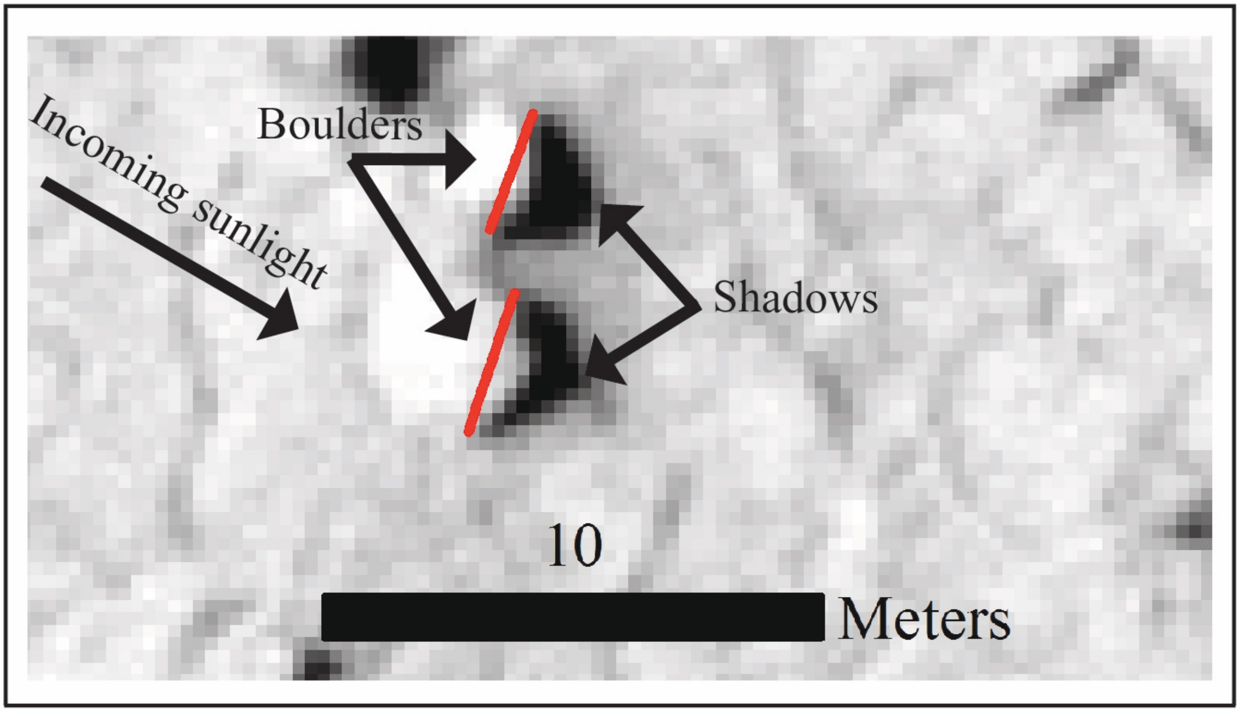

Figure 6. Example boulder width measurements (red).

To determine patterns in size frequency distribution, we plot boulder size versus distance along the respective flowline. Additionally, we separate boulder sizes via arbitrary binning and statistical clustering methods to reveal any individual areas of boulder size distribution.

To compare these results with those on terrestrial debris-covered glaciers, we performed a pilot study of boulder breakdown rates in the McMurdo Dry Valleys, Antarctica. Using high-resolution images and LiDAR (Light Detection and Ranging) and the previously discussed process of boulder measurement, we performed this analysis to both assess the efficacy of our methods and provide continued support for the use of the Antarctic Dry Valleys as a martian analogue. We used 200-m long bins to display and understand size-frequency distributions, plotting the 95th percentile and median values versus distance down-glacier of 1,000 boulders (**Fig. 10**).

B. Surface ridges

At the core of this surface ridge investigation is the testing of both new approaches and the expansion of previous methodologies, including those used by Grindrod et al. (2011). We employed methods of spectral analysis to evaluate potential signals reflected in surface ridges on LDA and Mullins and Friendman Glaciers in the McMurdo Dry Valleys. A map of the locations of our LDA used for ridge analysis is presented in **Figure 7**.

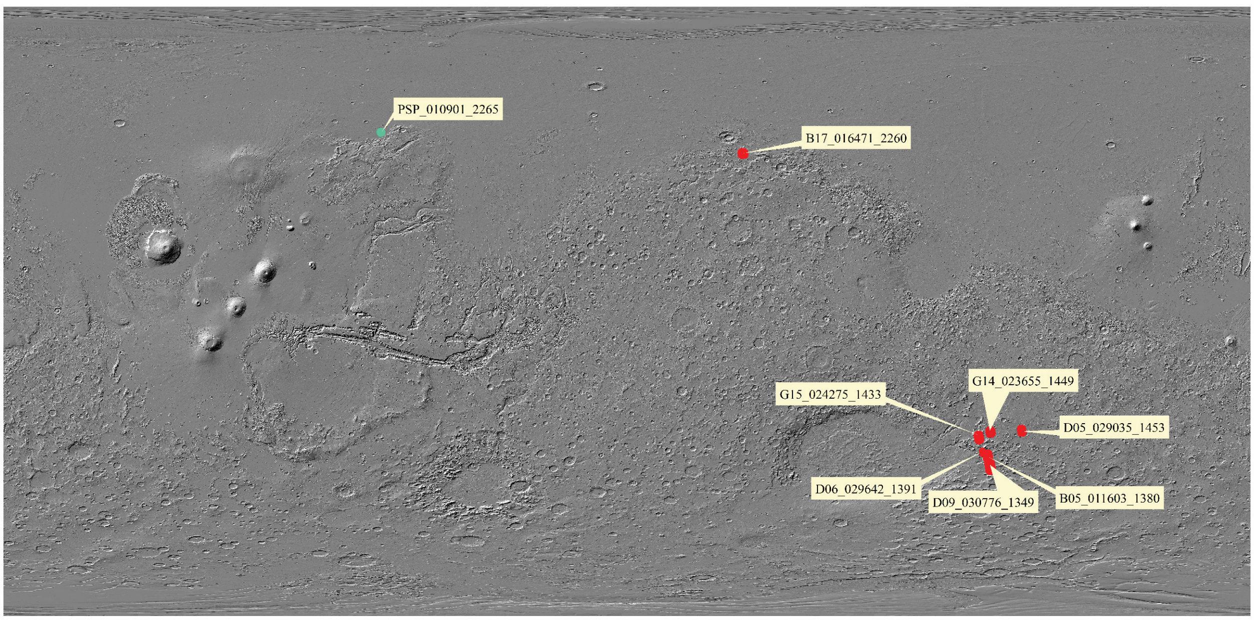

Figure 7. Map of our LDA study locations (red) and Grindrod et al. (2011) LDA study location (blue).

Using CTX stereo digital elevation models (DEMs), we contoured LDA at an interval of 100 m in ArcMap to locate the highest convex flow path. We then used the interpolate line feature to produce three adjacent lines along the determined path parallel to direction of ice flow (**Fig. 8**).

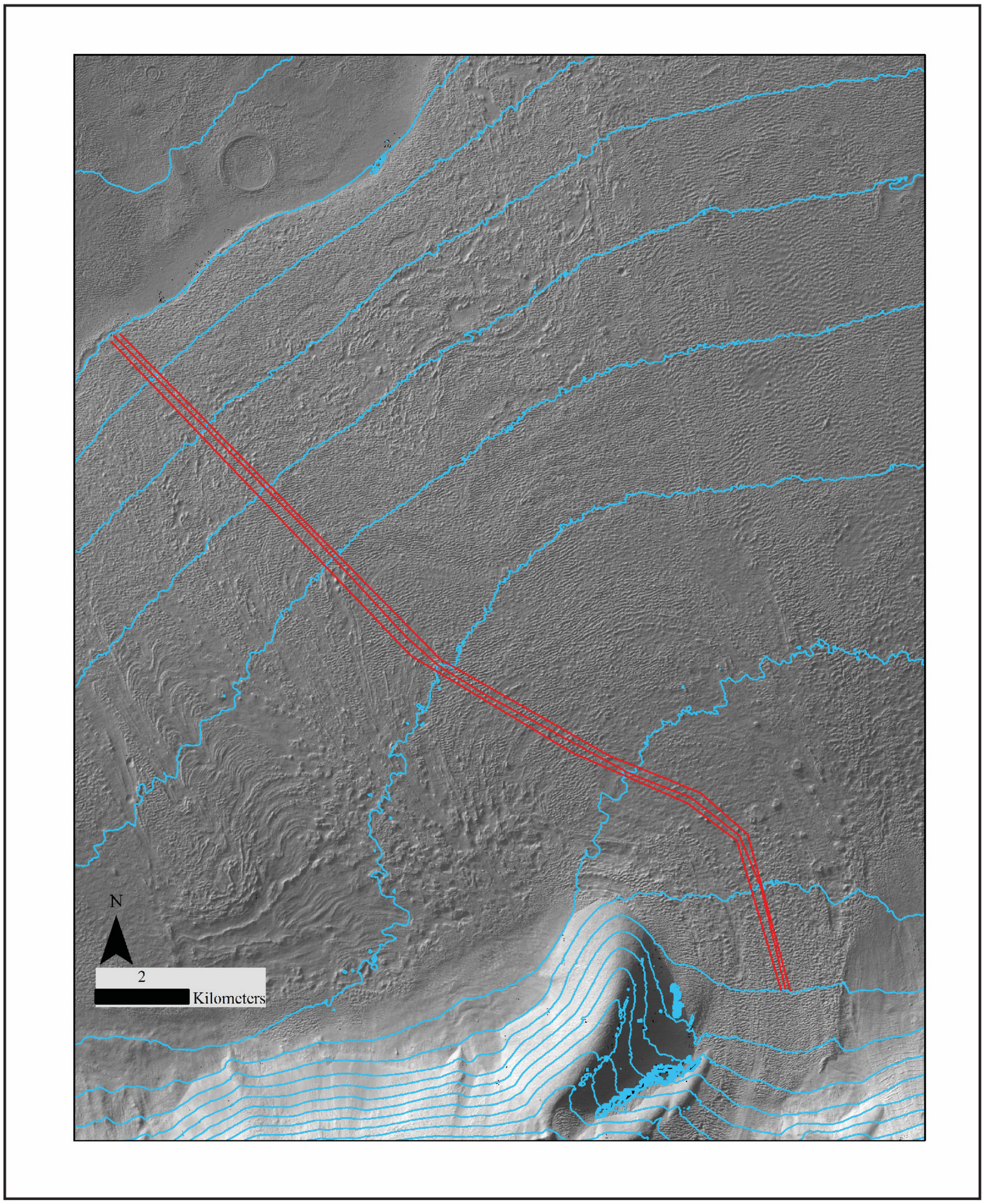

Figure 8. Example contour (blue) and paths (red) on LDA D09_030776_1349

Finally, we created topographic profile graphs from these 3D features and exported this data to average the values across these three lines and conduct various forms of analysis. These forms include the (1) plotting of slope and elevation versus distance down-glacier (2) use of Fourier transforms (FFT) to breakdown slope and elevation data into different frequencies (3) use of peak analysis (presented as histograms) to display the frequency of distances between peaks in elevation (**Fig. 12**). In all of these cases, the elevation and distance data used was the average of three paths.

To produce slope values, we calculated the instantaneous rate of change at each point of detrended elevation with its distance along the LDA path. We then plotted these slope values versus distance down-glacier (**Fig. 9a**). To display and interpret elevation data, we simply plotted detrended elevation versus distance down-glacier (**Fig. 9b**).

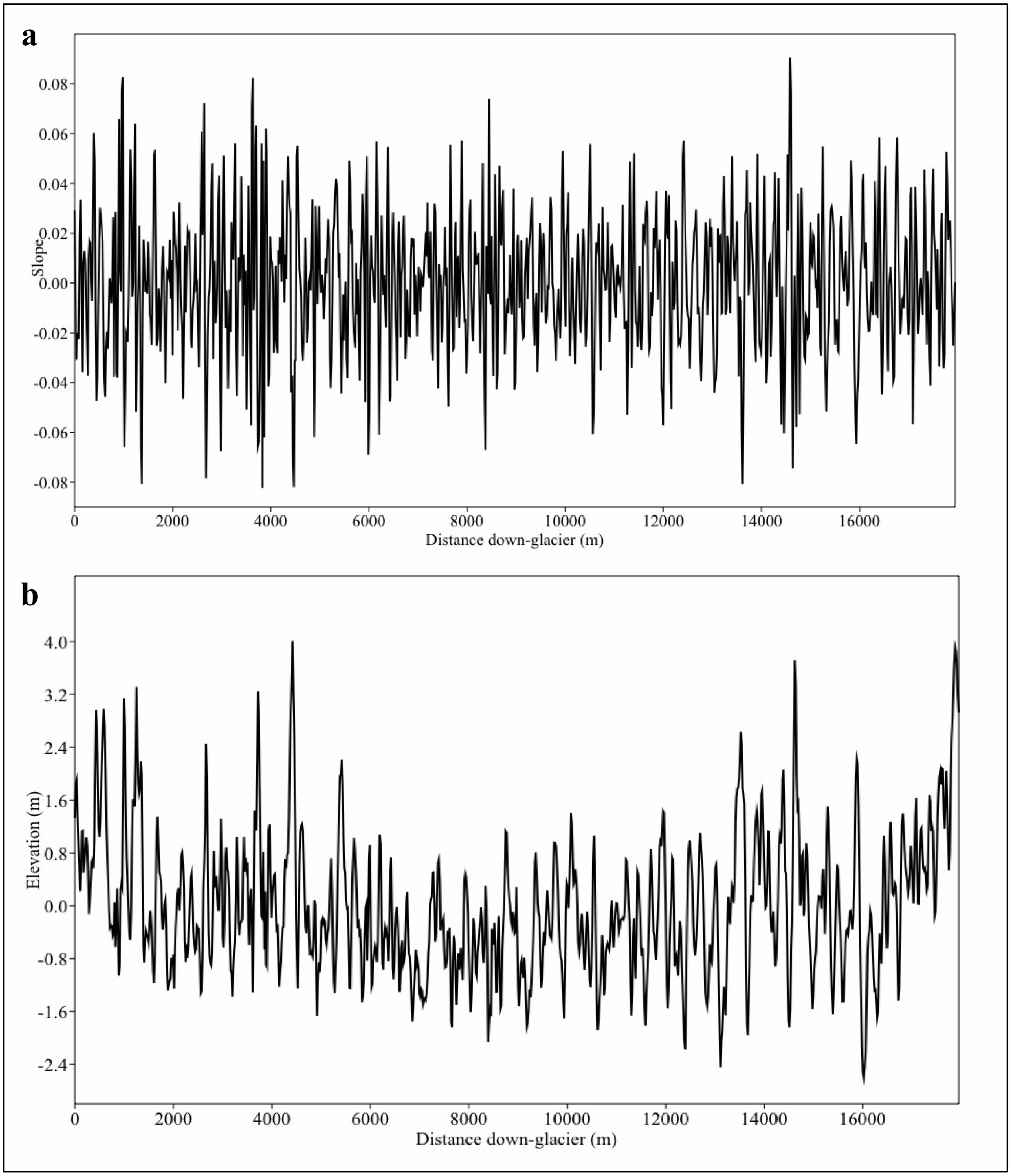

Figure 9. Results of topographic analysis for image LDA D09_030776_1349. (**a**) Shows slope versus distance down-glacier. (**b**) Shows elevation versus distance down-glacier.

To generate a histogram of the distance between peaks versus frequency, we removed the trend from the elevation data for a given LDA flow path by subtracting the linear regression line from the data. We used MATLAB to calculate the frequency of peaks in the detrended elevation data and the distances between these peaks. An example histogram produced by this method is provided in **Fig. 12**.

We used both MATLAB and PAST to produce spectrums of frequency and power values. The elevation data points obtained from each flow path were evenly spaced with respect to distance along the path, making FFT a useful form of spectral analysis. Frequency is in units of m^{-1} in these graphical representations.

IV. Results

We present results for methods of effectively analyzing surface ridges, boulder breakdown relationships on LDA, CCF, and Mullins Valley glacial formations, and patterns of surface ridges on LDA.

A. Surface debris methodology

One of the primary goals of this study was to explore potential methods of surface morphology analysis. While HiRISE images were most useful for accurate boulder measurements, CTX stereo images proved more effective for ridge analysis. CTX observations provided a bigger-picture view of the terrain, thereby reducing the noise of small-scale features reflected in HiRISE data.

The use of peak analysis proved effective in identifying a clear short wavelength signal ranging from ~100-200 m consistently across all LDA measured (**Fig. 12**).

The use of power spectrums of elevation profiles to describe the distribution of power into frequency components for a given profile resulted in data useful for characterizing ridges and the relationships between LDA. The employment of this method decomposed a complex elevation profile in terms of spatial frequency, providing a clearer view of our spatial domain of interest.

While the Grindrod et al. (2011) study of LDA topographic features relies on slope profiles and corresponding power spectra to identify and interpret ridges, we found that the data smoothing required to produce a meaningful result from slope values distorted the data beyond reasonable representation. Consequently, in the case of our methods and examined LDA, slope analysis did not provide convincing insight into ridge frequency, distribution, or origin.

B. Boulders

A preliminary study of boulder breakdown rates on Mullins Valley debris-covered glacier in the hyper-arid, hypo-thermal thermal environment of the Antarctic Dry Valleys shows a distinct decrease down to a minimum size (**Fig. 10a**). We attribute this minimum size to either an equilibrium boulder size or image resolution limitations.

Results from LDA, LVF, and CCF (**Fig. 10b-d**) thus far present three general cases of boulder size distribution: (1) profiles most consistent with exponential decay, exhibiting a clear decrease in size with distance down-glacier, (2) a relatively peaked profile, and (3) a scattered distribution without a clear signal.

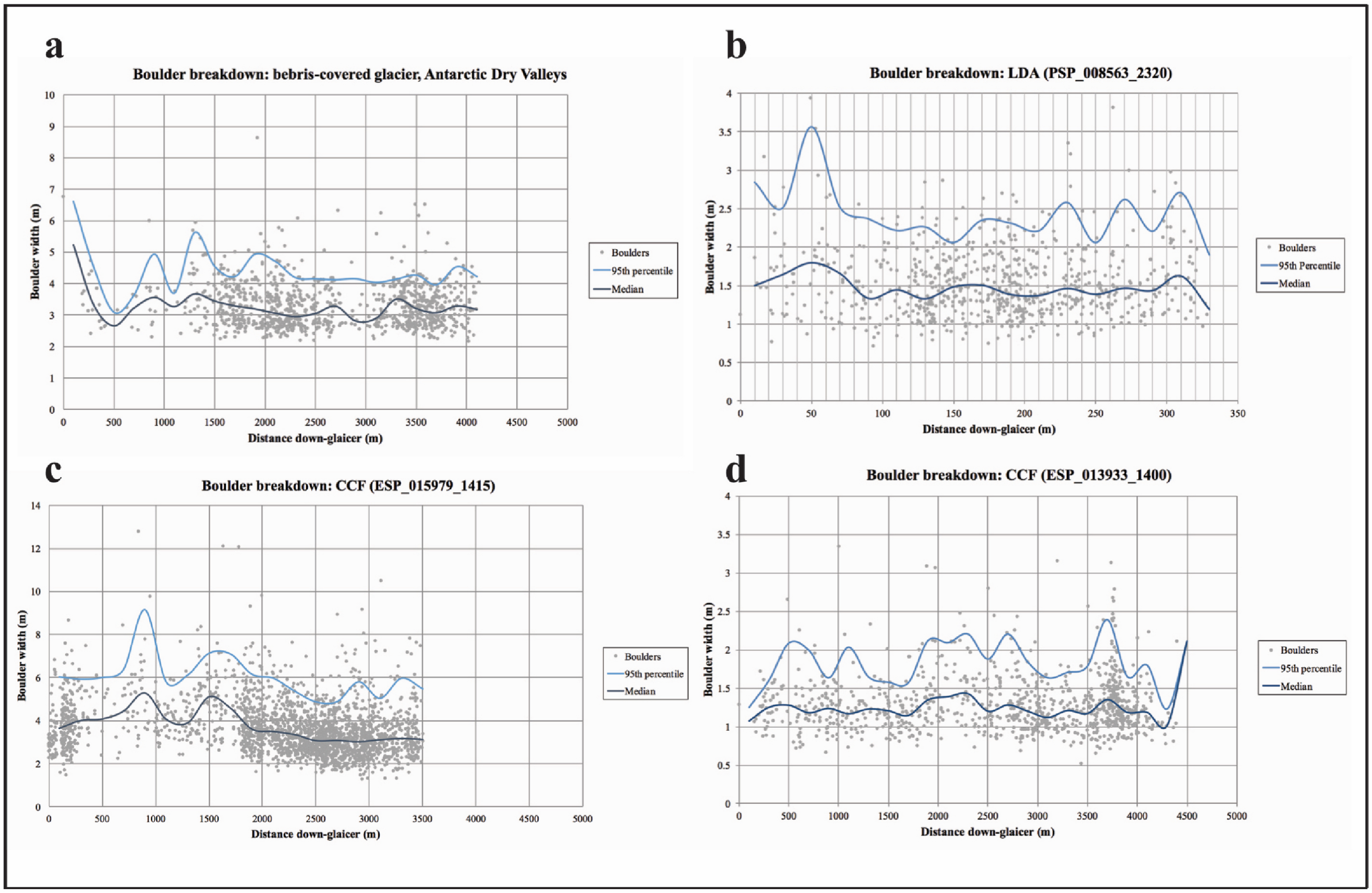

Figure 10. Plots of boulder width versus distance down-glacier for (**a**) Mullins Valley glacier (exponential), (**b**) LDA (peaked), (**c**) CCF (exponential), and (**d**) CCF (scattered).

C. Surface ridges

Through the analysis of power spectrums, we identified a potential widespread long wavelength signal on the order of ~1 km. However, our results over five sample (**Fig. 11**) do present a large range of periodic signals, with peak frequencies ranging from ~1,160 km (image D09_030776_1349) to ~337 m (image B17_016471_2260).

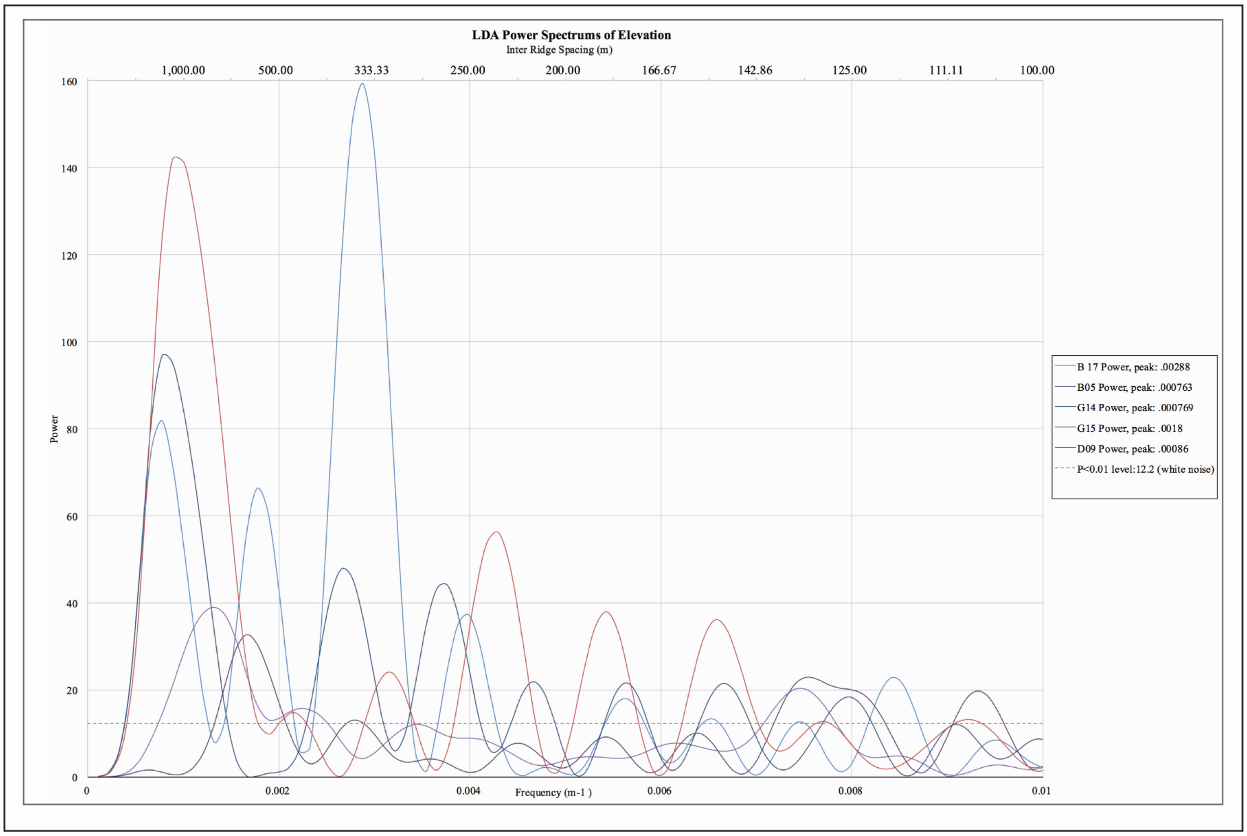

Figure 11. Power spectra of five LDA elevation profiles. Each elevation profile was averaged over three paths. Peak values represent peak freaquency for the respective LDA spectra. Grey dashed line represents estimated noise.

Our frequency histograms indicated a clear, widespread short wavelength on the order of 100-200 m. **Figure 12** presents sample results (image D09_030776_1349) in both large and small bins.

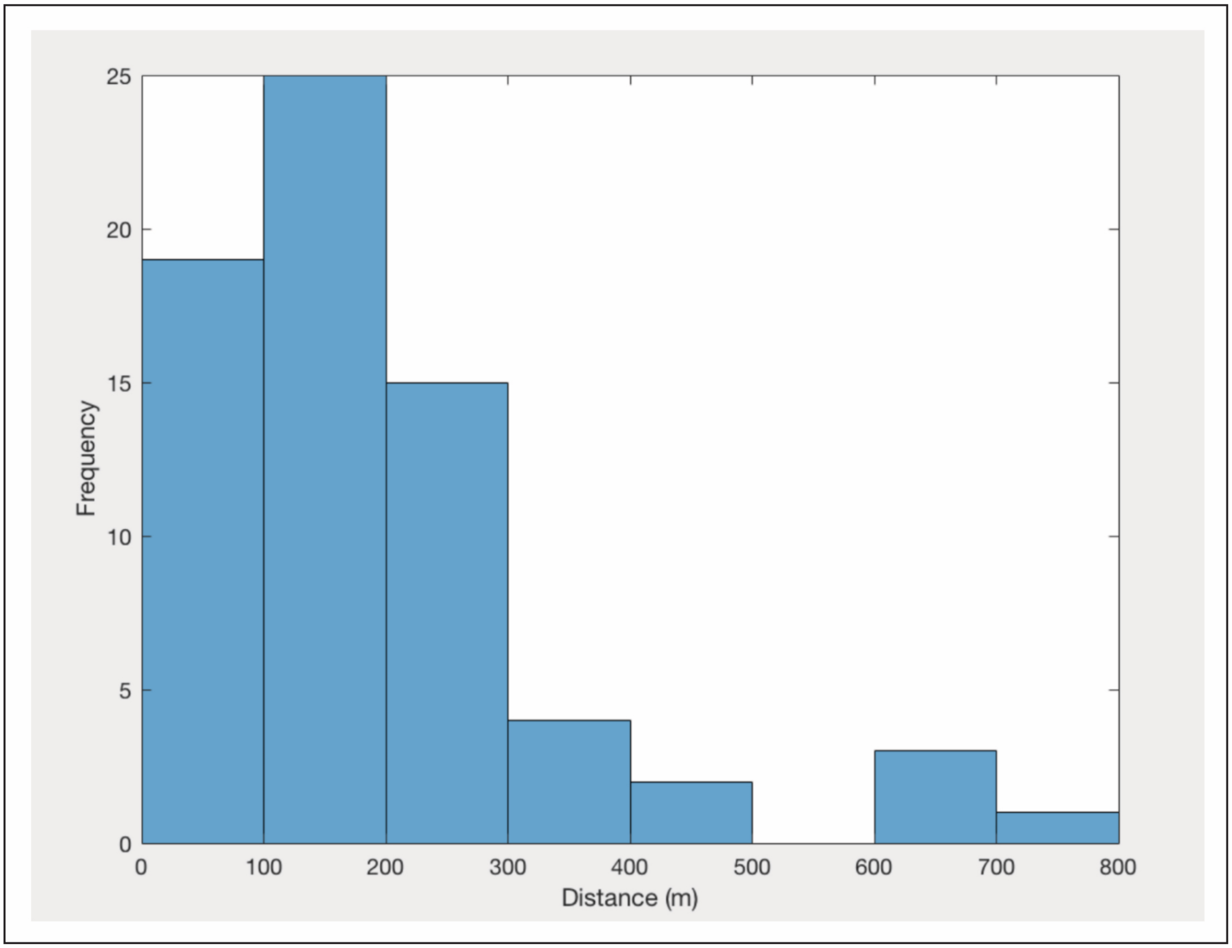

Figure 12. Histogram showing distances between peaks in elevation for D09_030776_1349.

V. Discussion

Noting that mechanisms of LDA ice and debris cover emplacement are presently poorly understood, the study of the temporal relationships between surface features like boulders and ridges and ice deposition could help explain LDA formation history. We explore the potential connections between these features and evaluate the use of surface morphology as a source of information for understanding martian mid-latitude glacial emplacement. We first address boulder breakdown rates as a function of glacial movement–an approach for which a number of analogues effective terrestrial studies exist (Putkonen et al., 2014; Golombek et al., 2003). We then address the implications of our results for ridge relationships and formation mechanisms, completing this discussion with an assessment of their potential as a climate record. We end by both addressing the significance of our results and acknowledging their limitations, highlighting our new contributions to the study of LDA formation and calling for continued investigation.

A. Boulders

In addressing boulder breakdown results, it is useful to understand the processes that govern boulder weathering on Mars. Due to current martian atmospheric and climatic conditions, most weathering processes active affecting landforms on Earth cannot presently function on Mars (Malin, 1974). However, some processes observed in similar terrestrial environments may be active or have been in the past on Mars. For example, studies indicate that salt weathering occurs in the Antarctic Dry Valleys (Peckham, 1972; Horowitz et al., 1969) and could play an important role in martian weathering processes (Malin, 1974). Weathering in the ADV dominantly acts through physical processes (Claridge, 1965; Kelly and Zumberge, 1961) and thus it is likely that the same holds true in the analogous martian climate.

Following from the established concept that weathering processes should reduce boulder size over time (Putkonen et al., 2014), we expect the observed decrease in boulder size down-glacier. Weathering mechanisms that may be active in breaking down boulders include aeolian processes (Arvidson et al., 1979; Bishop 2011), salt-induced rock fragmentation (Jagoutz 2006; Malin 1974), insolation-related thermal stress (Eppes et al., 2015), and fragmentation via meteorite impact (Genge 2017). Study citing surface and orbital observations suggests that erosion during the Amazonian occurred primarily through aeolian processes and was likely orders of magnitude slower than ancient erosion rates (Levy et al., 2016).

Our three resulting categories of boulder distribution each convey information about potential LDA, CCF, and LVF flow history. The generally exponential distribution (consistent with Mullins glacier results) indicates that glacial debris transport on martian landforms may closely resemble terrestrial processes. In this case we can infer a relationship of relative change between boulder breakdown and glacier flow over time. A peaked distribution presents a notably interesting case as it tells us not only about possible flow history, but also the nature of debris transport. As previously discussed in detail, this pattern reflects pulses in glaciation, suggesting episodic glacial emplacement. Furthermore, this distribution may indicate a method of englacial debris transport similar to that which has been observed on terrestrial glaciers (Mackay et al., 2014).

Though current boulder results do not provide a conclusive answer regarding LDA emplacement process, our study thus far indicates that boulder breakdown rates could be useful in constraining LDA flow history. Notably, each boulder size distribution reveals a population bundle of the largest boulders inside the total respective sample size within the first 1 km along the flow line. It is possible that this reflects an emplacement history wherein the glacier flowed, transporting boulders until accumulation ceased. After flow stopped, new boulders delivered from the headwall consequently did not travel far, actively rolling to their current position or transported at extremely slow rates.

These preliminary boulder results do not yield a widespread, repeating pattern across LDA, LVF, and CCF formations. However, they do suggest that boulder sizes are distinguishable as a function down-glacier (along our determined flow path), decreasing in diameter with distance from the accumulation zone.

B. Ridges

Frequency-domain analysis has proven to be a successful method of characterizing the frequency content of a wide-range of geologic signals (e.g. Ma et al., 2017, Ojha et al., 2015). In this study we produce periodograms that effectively highlight the relative strength of LDA and terrestrial glacier frequency components. We performed this analysis with the goal of finding (or not finding) morphological evidence of glacial emplacement events.

In the search for a potential climate record, our observation consistent with terrestrial results (Mackay et al. 2014) that not all surface ridges (if any, in the case of LDA) are associated with climate changes indicates a diverse interaction of geomorphic processes on LDA. Many of our peak frequency distributions exist in the range of long wavelength (700-1800 m) features identified by (Grindrod et al., 2011). The finding of a possible signal present in both the southern hemisphere LDA ridges (Eastern Hellas) and northern hemisphere LDA ridges (Grindrod et al., 2011 study located north-west of Tempe Terra/Mareotis Fossae) could indicate the reflection of a global climate change role in ridge formation. However, our current results (**Fig. 11**) present a frequency distribution too broad for an identification of a single wavelength or reasonable range of wavelengths that could definitively be linked to a climate signal. To further characterize ridge wavelengths and relationships, a continuation of this study will involve further LDA measurements and power spectrum analysis.

An additional, useful next-step would be to map these features to better understand ridge types and relationships. If we aim to evaluate the potential of LDA ridges as a record of climate information, we must first understand mechanisms of ridge development and LDA structure.

VI. Conclusions

A. Boulders and ridges as climate records

Our boulder results confirm that these glacial landforms (LDA, CCF, LVF) have the ability to transport debris that may be demarcate climate cycles. These observations are consistent with terrestrial results, providing continued support for the use of the Antarctic Dry Valleys as a relevant analogue to martian environmental conditions. Most notably, our boulder size evolution patterns indicate the possibility of episodic glaciation during the late Amazonian and the potentially significant role of englacial debris transport.

Our surface ridge results suggest that a long wavelength signal may be present on the order of ~1 km. Supporting boulder results, these debris bands may indicate episodes of glaciation and englacial transport processes. Our results do not provide conclusive evidence of these processes, but rather support the continued investigation of surface morphology potential.

B. Significance

From the detailed drawings of Schiaparelli to the images produced by the Mars Reconnaissance Orbiter, our understanding of the role of water on Mars has experienced constant evolution. The atmosphere and climate of Mars present important proxies for ideas regarding the distribution and stability of water and connecting these ideas to possible life. Because water is essential to the existence of life as we currently understand it, surface water ice has important implications for our ongoing investigation into questions of martian life.

The study of LDA formation history provides valuable information not only about what Mars looked like in the past and the possibility of past life, but also about potential locations for future landed missions. The mid-to-low latitudes of Mars are more easily accessible sites for exploration, making the finding of a potential climate record in these locations potentially very useful.

A comprehensive picture of water on Mars is essential to challenging and expanding our human perceptions of life and other planets. The discovery of liquid water below the surface and/or evidence of life on Mars by future missions would undoubtedly provide vast insight into the universal distribution of life. However, should future research and missions conclusively show us that life never existed on Mars, we would gain a different, but similarly invaluable perspective: a challenge of our present ideas of the fundamental requirements for the existence of life.

C. Areas for future study

Though recent image and radar data has significantly advanced work with martian LDA, there exists extensive need for additional research. A key step in progressing our understanding of this other planet is an understanding of our own. Through continued study of analogue sites such as those in the Antarctic Dry Valleys, we gain deeper insight into not only features on Mars, but also how we may effectively study them. New morphological and structural data from these analogue sites in the ADV provides an increasingly full picture of the nature of both planetary environments. Specific to our work, further study of how much material conveys solely as supraglacial debris relative to the amount that falls in areas of ice accumulation and experiences englacial transport is integral to advancing understanding of debris transport and origin. Mullins and Friedman glaciers are useful sites for this continued study, expanding on the work of Mackay et al. 2014.

Specific to the study of Mars and its ice-rich features, the use of toolsets including CTX and HiRISE cameras combined with instruments such as SHARAD continuously produces new insight into the characteristics of features such as LDA. From initial LDA observations produced by Viking orbiter data to recent high-resolution images and capability to investigate ice-rich deposits through kilometers of depth, new technology constantly opens up new areas to study.

Evidenced by this study, ridges on debris-covered glaciers in many ways remain enigmatic. Continued investigation into these ridges focused on causal mechanisms, relationships between ridges, and potential links to climate variations would be useful in characterizing glacier morphology and potential Amazonian climate change. While future study can and should employ numerous different approaches, expanded mapping and evaluation of new methods of ridge analysis would be productive next-steps in broadening and further developing this research.

One of the most important and undeniably compelling future fields of study related to Mars is field work itself. The possibility of liquid ice on Mars, whether existing in the subsurface today or only in the past and preserved in present-day features, provokes questions regarding the ability of life to exist on the planet. Specifically, the presence of water ice at mid-latitudes opens up the opportunity for future landed missions in these areas, providing a potential resource and sites for climate study.

While recent technological development has propelled significant advancement of the understanding of LDA and Mars as a whole, we have only just begun to explore this diverse planet. As a forefront for new research, Mars presents both an ambitious and exciting territory for study, and with vast questions unanswered, there remains much work to be done.

REFERENCES

Abramov, Oleg, and Stephen J. Mojzsis. 2016. "Thermal Effects of Impact Bombardments on Noachian Mars." *Earth and Planetary Science Letters* 442 (May): 108–20. doi:10.1016/j.epsl.2016.02.035.

Ackert, Robert P. 1998. "A Rock Glacier/Debris-Covered Glacier System at Galena Creek, Absaroka Mountains, Wyoming." *Geografiska Annaler. Series A, Physical Geography* 80 (3/4): 267–76.

Arcone, Steven A., Michael L. Prentice, and Allan J. Delaney. 2002. "Stratigraphic Profiling with Ground-Penetrating Radar in Permafrost: A Review of Possible Analogs for Mars: REVIEW OF POSSIBLE ANALOGS FOR MARS." *Journal of Geophysical Research: Planets* 107 (E11): 18-1-18–14. doi:10.1029/2002JE001906.

Armstrong, John C., Conway B. Leovy, and Thomas Quinn. 2004. "A 1 Gyr Climate Model for Mars: New Orbital Statistics and the Importance of Seasonally Resolved Polar Processes." *Icarus* 171 (2): 255–71. doi:10.1016/j.icarus.2004.05.007.

Arvidson, R., E. Guinness, and S. Lee. 1979. "Differential Aeolian Redistribution Rates on Mars." *Nature* 278 (5704): 533–35. doi:10.1038/278533a0.

Atkins, C.B., P.J. Barrett, and S.R. Hicock. 2002. "Cold Glaciers Erode and Deposit: Evidence from Allan Hills, Antarctica." *Geology* 30 (7): 659. doi:10.1130/0091-7613(2002)030<0659:CGEADE>2.0.CO;2.

Augustinus, P. C., and M. J. Selby. 1990. "Rock Slope Development in McMurdo Oasis, Antarctica, and Implications for Interpretations of Glacial History." *Geografiska Annaler. Series A, Physical Geography* 72 (1): 55. doi:10.2307/521237.

Baker, V. R. 2006. "Geomorphological Evidence for Water on Mars." *Elements* 2 (3): 139–43. doi:10.2113/gselements.2.3.139.

———. n.d. "Water and the Martian Landscape." *Nature*, 412(6843), 228-36. doi:http://dx.doi.org.ezproxy.lib.utexas.edu/10.1038/35084172.

Banks, Maria E., Nicholas P. Lang, Jeffrey S. Kargel, Alfred S. McEwen, Victor R. Baker, John A. Grant, Jon D. Pelletier, and Robert G. Strom. 2009. "An Analysis of Sinuous Ridges in the Southern Argyre Planitia, Mars Using HiRISE and CTX Images and MOLA Data." *Journal of Geophysical Research* 114 (E9). doi:10.1029/2008JE003244.

Berman, Daniel C., David A. Crown, and Emily C.S. Joseph. 2015. "Formation and Mantling Ages of Lobate Debris Aprons on Mars: Insights from Categorized Crater Counts." *Planetary and Space Science* 111 (June): 83–99. doi:10.1016/j.pss.2015.03.013.

Bishop, Mark A. 2011. “Aeolian Scours as Putative Signatures of Wind Erosion and Sediment Transport Direction on Mars.” *Geomorphology* 125 (4): 569–74. doi:10.1016/j.geomorph.2010.10.029.

Burger, K.C., J.J. Degenhardt, and J.R. Giardino. 1999. “Engineering Geomorphology of Rock Glaciers.” *Geomorphology* 31 (1–4): 93–132. doi:10.1016/S0169-555X(99)00074-4.

Carr, Michael H., and Gerald G. Schaber. 1977. “Martian Permafrost Features.” *Journal of Geophysical Research* 82 (28): 4039–54. doi:10.1029/JS082i028p04039.

Claridge, G. G. C. 1965. “The Clay Mineralogy and Chemistry of Some Soils from the Ross Dependency, Antarctica.” *New Zealand Journal of Geology and Geophysics* 8 (2): 186–220. doi:10.1080/00288306.1965.10428107.

Colaprete, Anthony, and Bruce M. Jakosky. 1998. “Ice Flow and Rock Glaciers on Mars.” *Journal of Geophysical Research: Planets* 103 (E3): 5897–5909. doi:10.1029/97JE03371.

Costard, F., F. Forget, N. Mangold, and J. P. Peulvast. 2002. “Formation of Recent Martian Debris Flows by Melting of Near-Surface Ground Ice at High Obliquity.” *Science* 295 (5552): 110–13.

Craddock, Robert A., and Alan D. Howard. 2002. “The Case for Rainfall on a Warm, Wet Early Mars: RAINFALL ON MARS.” *Journal of Geophysical Research: Planets* 107 (E11): 21-1-21–36. doi:10.1029/2001JE001505.

Cravens, T. E., A. Rahmati, Jane L. Fox, R. Lillis, S. Bougher, J. Luhmann, S. Sakai, et al. 2017. “Hot Oxygen Escape from Mars: Simple Scaling with Solar EUV Irradiance: OXYGEN ESCAPE FROM MARS.” *Journal of Geophysical Research: Space Physics* 122 (1): 1102–16. doi:10.1002/2016JA023461.

Degenhardt, John J. 2003. “Subsurface Investigation of a Rock Glacier Using Ground-Penetrating Radar: Implications for Locating Stored Water on Mars.” *Journal of Geophysical Research* 108 (E4). doi:10.1029/2002JE001888.

Dickson, James L., and James W. Head. 2009. “The Formation and Evolution of Youthful Gullies on Mars: Gullies as the Late-Stage Phase of Mars’ Most Recent Ice Age.” *Icarus* 204 (1): 63–86. doi:10.1016/j.icarus.2009.06.018.

Dickson, James L., James W. Head, and Mikhail Kreslavsky. 2007. “Martian Gullies in the Southern Mid-Latitudes of Mars: Evidence for Climate-Controlled Formation of Young Fluvial Features Based upon Local and Global Topography.” *Icarus* 188 (2): 315–23. doi:10.1016/j.icarus.2006.11.020.

Eppes, Martha-Cary, Andrew Willis, Jamie Molaro, Stephen Abernathy, and Beibei Zhou. 2015. “Cracks in Martian Boulders Exhibit Preferred Orientations That Point to Solar-Induced Thermal Stress.” *Nature Communications* 6 (March): 6712. doi:10.1038/ncomms7712.

Fassett, C. I., J. S. Levy, J. L. Dickson, and J. W. Head. 2014. “An Extended Period of Episodic Northern Mid-Latitude Glaciation on Mars during the Middle to Late Amazonian: Implications for Long-Term Obliquity History.” *Geology* 42 (9): 763–66. doi:10.1130/G35798.1.

Fassett, Caleb I., James L. Dickson, James W. Head, Joseph S. Levy, and David R. Marchant. 2010. “Supraglacial and Proglacial Valleys on Amazonian Mars.” *Icarus* 208 (1): 86–100. doi:10.1016/j.icarus.2010.02.021.

Fastook, James L., James W. Head, and David R. Marchant. 2014. “Formation of Lobate Debris Aprons on Mars: Assessment of Regional Ice Sheet Collapse and Debris-Cover Armoring.” *Icarus* 228 (January): 54–63. doi:10.1016/j.icarus.2013.09.025.

Forget, F., R. M. Haberle, F. Montmessin, B. Levrard, and J. W. Head. 2006. “Formation of Glaciers on Mars by Atmospheric Precipitation at High Obliquity.” *Science* 311 (5759): 368–71.

Fox, Jane L., M. Benna, P. R. Mahaffy, and B. M. Jakosky. 2015. “Water and Water Ions in the Martian Thermosphere/Ionosphere: WATER AND WATER IONS ON MARS.” *Geophysical Research Letters* 42 (21): 8977–85. doi:10.1002/2015GL065465.

Frehner, Marcel, Anna Hui Mee Ling, and Isabelle Gärtner-Roer. 2015. “Furrow-and-Ridge Morphology on Rockglaciers Explained by Gravity-Driven Buckle Folding: A Case Study From the Murtèl Rockglacier (Switzerland): Rockglacier Furrow-and-Ridge Morphology Explained by Buckle Folding.” *Permafrost and Periglacial Processes* 26 (1): 57–66. doi:10.1002/ppp.1831.

Genge, Matthew J. 2017. “The Entry Heating and Abundances of Basaltic Micrometeorites.” *Meteoritics & Planetary Science*, February. doi:10.1111/maps.12830.

Golombek, M. P., A. F. C. Haldemann, N. K. Forsberg-Taylor, E. N. DiMaggio, R. D. Schroeder, B. M. Jakosky, M. T. Mellon, and J. R. Matijevic. 2003. “Rock Size-Frequency Distributions on Mars and Implications for Mars Exploration Rover Landing Safety and Operations: ROCK SIZE-FREQUENCY DISTRIBUTIONS ON MARS.” *Journal of Geophysical Research: Planets* 108 (E12). doi:10.1029/2002JE002035.

Grindrod, Peter M., and Stephen A. Fawcett. 2011. “Possible Climate-Related Signals in High-Resolution Topography of Lobate Debris Aprons in Tempe Terra, Mars: MARTIAN LOBATE DEBRIS APRON TOPOGRAPHY.” *Geophysical Research Letters* 38 (19): n/a-n/a. doi:10.1029/2011GL049295.

Head, J. W., G. Neukum, R. Jaumann, H. Hiesinger, E. Hauber, M. Carr, P. Masson, et al. 2005. “Tropical to Mid-Latitude Snow and Ice Accumulation, Flow and Glaciation on Mars.” *Nature* 434 (7031): 346–51. doi:10.1038/nature03359.

Head, James W., and David R. Marchant. 2014. “The Climate History of Early Mars: Insights from the Antarctic McMurdo Dry Valleys Hydrologic System.” *Antarctic Science* 26 (6): 774–800. doi:10.1017/S0954102014000686.

Head, James W., David R. Marchant, James L. Dickson, Ailish M. Kress, and David M. Baker. 2010. "Northern Mid-Latitude Glaciation in the Late Amazonian Period of Mars: Criteria for the Recognition of Debris-Covered Glacier and Valley Glacier Landsystem Deposits." *Earth and Planetary Science Letters* 294 (3–4): 306–20. doi:10.1016/j.epsl.2009.06.041.

Hodges, R. Richard. 2002. "The Rate of Loss of Water from Mars." *Geophysical Research Letters* 29 (3). doi:10.1029/2001GL013853.

Horowitz, N. H., A. J. Bauman, R. E. Cameron, P. J. Geiger, J. S. Hubbard, G. P. Shulman, P. G. Simmonds, and K. Westberg. 1969. "Sterile Soil from Antarctica: Organic Analysis." *Science* 164 (3883): 1054–56. doi:10.1126/science.164.3883.1054.

Hubbard, B., C. Souness, and S. Brough. 2014. "Glacier-like Forms on Mars." *The Cryosphere* 8 (6): 2047–61. doi:10.5194/tc-8-2047-2014.

Humlum, Ole. 1998. "The Climatic Significance of Rock Glaciers." *Permafrost and Periglacial Processes* 9 (4): 375–95. doi:10.1002/(SICI)1099-1530(199810/12)9:4<375::AID-PPP301>3.0.CO;2-0.

Jagoutz, Emil. 2006. "Salt-Induced Rock Fragmentation on Mars: The Role of Salt in the Weathering of Martian Rocks." *Advances in Space Research* 38 (4): 696–700. doi:10.1016/j.asr.2005.07.070.

JeongAhn, Youngmin, and Renu Malhotra. 2015. "The Current Impact Flux on Mars and Its Seasonal Variation." *Icarus* 262 (December): 140–53. doi:10.1016/j.icarus.2015.08.032.

Kelly, William C., and James H. Zumberge. 1961. "Weathering of a Quartz Diorite at Marble Point, McMurdo Sound, Antarctica." *The Journal of Geology* 69 (4): 433–46.

Konrad, S. K., N. F. Humphrey, E. J. Steig, D. H. Clark, N. Potter, and W. T. Pfeffer. 1999. "Rock Glacier Dynamics and Paleoclimatic Implications." *Geology* 27 (12): 1131. doi:10.1130/0091-7613(1999)027<1131:RGDAPI>2.3.CO;2.

Kreslavsky, M. A., and J. W. Head. 2005. "Mars at Very Low Obliquity: Atmospheric Collapse and the Fate of Volatiles: MARS AT LOW OBLIQUITY." *Geophysical Research Letters* 32 (12): n/a-n/a. doi:10.1029/2005GL022645.

Kreslavsky, Mikhail A., James W. Head, and David R. Marchant. 2008a. "Periods of Active Permafrost Layer Formation during the Geological History of Mars: Implications for Circum-Polar and Mid-Latitude Surface Processes." *Mars Polar Processes: Atmosphere-Surface Interactions* 56 (2): 289–302. doi:10.1016/j.pss.2006.02.010.

———. 2008b. "Periods of Active Permafrost Layer Formation during the Geological History of Mars: Implications for Circum-Polar and Mid-Latitude Surface Processes." *Mars Polar Processes: Atmosphere-Surface Interactions* 56 (2): 289–302. doi:10.1016/j.pss.2006.02.010.

Kreslavsky, Mikhail A., John F. Mustard, Ralph E. Milliken, David R. Marchant, and James W. Head. 2003. "Recent Ice Ages on Mars." *Nature* 426 (6968): 797–802. doi:10.1038/nature02114.

Lahtela, H., V.-P. Kostama, J. Korteniemi, J. Raitala, and M. Aittola. 2011. “Mapping and Analysis of a Chain of Channeled Basins in the Eastern Rim Region of Hellas Basin, Mars.” *Planetary and Space Science* 59 (11–12): 1195–1209. doi:10.1016/j.pss.2010.09.009.

Laskar, J., A.C.M. Correia, M. Gastineau, F. Joutel, B. Levrard, and P. Robutel. 2004. “Long Term Evolution and Chaotic Diffusion of the Insolation Quantities of Mars.” *Icarus* 170 (2): 343–64. doi:10.1016/j.icarus.2004.04.005.

Levy, Joseph S., Caleb I. Fassett, and James W. Head. 2016. “Enhanced Erosion Rates on Mars during Amazonian Glaciation.” *Icarus* 264 (January): 213–19. doi:10.1016/j.icarus.2015.09.037.

Levy, Joseph S., Caleb I. Fassett, James W. Head, Claire Schwartz, and Jaclyn L. Watters. 2014. “Sequestered Glacial Ice Contribution to the Global Martian Water Budget: Geometric Constraints on the Volume of Remnant, Midlatitude Debris-Covered Glaciers: Buried Martian Glaciers.” *Journal of Geophysical Research: Planets* 119 (10): 2188–96. doi:10.1002/2014JE004685
.

Levy, Joseph S., James W. Head, and David R. Marchant. 2009. “Cold and Dry Processes in the Martian Arctic: Geomorphic Observations at the Phoenix Landing Site and Comparisons with Terrestrial Cold Desert Landforms.” *Geophysical Research Letters* 36 (21). doi:10.1029/2009GL040634.

Levy, Joseph S., David R. Marchant, and James W. Head. 2006. “Distribution and Origin of Patterned Ground on Mullins Valley Debris-Covered Glacier, Antarctica: The Roles of Ice Flow and Sublimation.” *Antarctic Science* 18 (3). doi:10.1017/S0954102006000435.

Levy, J.S., J.W. Head, D.R. Marchant, J.L. Dickson, and G.A. Morgan. 2009. “Geologically Recent Gully–polygon Relationships on Mars: Insights from the Antarctic Dry Valleys on the Roles of Permafrost, Microclimates, and Water Sources for Surface Flow.” *Icarus* 201 (1): 113–26. doi:10.1016/j.icarus.2008.12.043.

Li, H, M Robinson, and D Jurdy. 2005. “Origin of Martian Northern Hemisphere Mid-Latitude Lobate Debris Aprons.” *Icarus* 176 (2): 382–94. doi:10.1016/j.icarus.2005.02.011.

Lucchitta, Baerbel K. 1984. “Ice and Debris in the Fretted Terrain, Mars.” *Journal of Geophysical Research* 89 (S02): B409. doi:10.1029/JB089iS02p0B409.

Ma, Chao, Stephen R. Meyers, and Bradley B. Sageman. 2017. “Theory of Chaotic Orbital Variations Confirmed by Cretaceous Geological Evidence.” *Nature* 542 (7642): 468–70. doi:10.1038/nature21402.

Mackay, Sean L., David R. Marchant, Jennifer L. Lamp, and James W. Head. 2014. “Cold-Based Debris-Covered Glaciers: Evaluating Their Potential as Climate Archives through Studies of Ground-Penetrating Radar and Surface Morphology: Cold-Based Debris-Covered Glaciers.” *Journal of Geophysical Research: Earth Surface* 119 (11): 2505–40. doi:10.1002/2014JF003178.

Madeleine, J.-B., F. Forget, James W. Head, B. Levrard, F. Montmessin, and E. Millour. 2009. "Amazonian Northern Mid-Latitude Glaciation on Mars: A Proposed Climate Scenario." *Icarus* 203 (2): 390–405. doi:10.1016/j.icarus.2009.04.037.

Malin, M.C. n.d. "Rock Populations as Indicators of Geologic Processes, in Reports to Planetary Geology and Geophysics Program." NASA Tech Memo., TM-4041, 502–504.

Malin, Michael C. 1974. "Salt Weathering on Mars." *Journal of Geophysical Research* 79 (26): 3888–94. doi:10.1029/JB079i026p03888.

Mangold, N., and P. Allemand. 2001. "Topographic Analysis of Features Related to Ice on Mars." *Geophysical Research Letters* 28 (3): 407–10. doi:10.1029/2000GL008491.

Mangold, Nicolas. 2005. "High Latitude Patterned Grounds on Mars: Classification, Distribution and Climatic Control." *Icarus* 174 (2): 336–59. doi:10.1016/j.icarus.2004.07.030.

Marchant, David R., and James W. Head. 2007. "Antarctic Dry Valleys: Microclimate Zonation, Variable Geomorphic Processes, and Implications for Assessing Climate Change on Mars." *Icarus* 192 (1): 187–222. doi:10.1016/j.icarus.2007.06.018.

Mellon, Michael T., and Bruce M. Jakosky. 1995. "The Distribution and Behavior of Martian Ground Ice during Past and Present Epochs." *Journal of Geophysical Research* 100 (E6): 11781. doi:10.1029/95JE01027.

Nakamura, Takasumi, and Eiichi Tajika. 2003. "Climate Change of Mars-like Planets due to Obliquity Variations: Implications for Mars: CLIMATE CHANGE OF MARS." *Geophysical Research Letters* 30 (13). doi:10.1029/2002GL016725.

Ojha, Lujendra, Mary Beth Wilhelm, Scott L. Murchie, Alfred S. McEwen, James J. Wray, Jennifer Hanley, Marion Massé, and Matt Chojnacki. 2015. "Spectral Evidence for Hydrated Salts in Recurring Slope Lineae on Mars." *Nature Geoscience* 8 (11): 829–32. doi:10.1038/ngeo2546.

Parsons, Reid, and John Holt. 2016. "Constraints on the Formation and Properties of a Martian Lobate Debris Apron: Insights from High-Resolution Topography, SHARAD Radar Data, and a Numerical Ice Flow Model: EURIPUS MONS LDA ANALYSIS." *Journal of Geophysical Research: Planets* 121 (3): 432–53. doi:10.1002/2015JE004927.

Peckham, Alan E. 1972. "Arid Lands in Perspective." *Journal of the American Water Resources Association* 8 (4): 838–838a. doi:10.1111/j.1752-1688.1972.tb05231.x.

Phillips, R. J., M. T. Zuber, S. E. Smrekar, M. T. Mellon, J. W. Head, K. L. Tanaka, N. E. Putzig, et al. 2008. "Mars North Polar Deposits: Stratigraphy, Age, and Geodynamical Response." *Science* 320 (5880): 1182–85. doi:10.1126/science.1157546.

Pierce, Timothy L., and David A. Crown. 2003. “Morphologic and Topographic Analyses of Debris Aprons in the Eastern Hellas Region, Mars.” *Icarus* 163 (1): 46–65. doi:10.1016/S0019-1035(03)00046-0.

Plaut, Jeffrey J., Ali Safaeinili, John W. Holt, Roger J. Phillips, James W. Head, Roberto Seu, Nathaniel E. Putzig, and Alessandro Frigeri. 2009. “Radar Evidence for Ice in Lobate Debris Aprons in the Mid-Northern Latitudes of Mars: RADAR EVIDENCE FOR MID-LATITUDE MARS ICE.” *Geophysical Research Letters* 36 (2): n/a-n/a. doi:10.1029/2008GL036379.

Potter, N., E. J. Steig, D. H. Clark, M. A. Speece, G. M. Clark, and Arika B. Updike. 1998. “Galena Creek Rock Glacier Revisited: New Observations on an Old Controversy.” *Geografiska Annaler. Series A, Physical Geography* 80 (3/4): 251–65.

Putkonen, Jaakko, Daniel Morgan, and Greg Balco. 2014. “Boulder Weathering in McMurdo Dry Valleys, Antarctica.” *Geomorphology* 219 (August): 192–99. doi:10.1016/j.geomorph.2014.05.012.

Salvatore, M.R., J.F. Mustard, J.W. Head, R.F. Cooper, D.R. Marchant, and M.B. Wyatt. 2013. “Development of Alteration Rinds by Oxidative Weathering Processes in Beacon Valley, Antarctica, and Implications for Mars.” *Geochimica et Cosmochimica Acta* 115 (August): 137–61. doi:10.1016/j.gca.2013.04.002.

Segschneider, J., B. Grieger, H.U. Keller, F. Lunkeit, E. Kirk, K. Fraedrich, A. Rodin, and R. Greve. 2005. “Response of the Intermediate Complexity Mars Climate Simulator to Different Obliquity Angles.” *Planetary and Space Science* 53 (6): 659–70. doi:10.1016/j.pss.2004.10.003.

Squyres, Steven W. 1979. “The Distribution of Lobate Debris Aprons and Similar Flows on Mars.” *Journal of Geophysical Research* 84 (B14): 8087. doi:10.1029/JB084iB14p08087.

Stuurman, C. M., G. R. Osinski, J. W. Holt, J. S. Levy, T. C. Brothers, M. Kerrigan, and B. A. Campbell. 2016. “SHARAD Detection and Characterization of Subsurface Water Ice Deposits in Utopia Planitia, Mars: SHARAD DETECTION OF ICE UTOPIA PLANITIA.” *Geophysical Research Letters* 43 (18): 9484–91. doi:10.1002/2016GL070138.

Toon, Owen B., James B. Pollack, William Ward, Joseph A. Burns, and Kenneth Bilski. 1980. “The Astronomical Theory of Climatic Change on Mars.” *Icarus* 44 (3): 552–607. doi:10.1016/0019-1035(80)90130-X.

Toon, Owen B., Teresa Segura, and Kevin Zahnle. 2010. “The Formation of Martian River Valleys by Impacts.” *Annual Review of Earth and Planetary Sciences* 38 (1): 303–22. doi:10.1146/annurev-earth-040809-152354.

Whalley, W. Brian. 2003. “Rock Glaciers and Protalus Landforms: Analogous Forms and Ice Sources on Earth and Mars.” *Journal of Geophysical Research* 108 (E4). doi:10.1029/2002JE001864.

Wordsworth, Robin D., Laura Kerber, Raymond T. Pierrehumbert, Francois Forget, and James W. Head. 2015. “Comparison of ‘warm and Wet’ and ‘cold and Icy’ Scenarios for Early Mars in a 3-D Climate Model: WARM AND WET VS. COLD AND ICY EARLY MARS.” *Journal of Geophysical Research: Planets* 120 (6): 1201–19. doi:10.1002/2015JE004787.

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